Conserving Caravaggio's

Crucifixion of Saint Andrew

A TECHNICAL STUDY

By Dean Yoder

Foreword 4
Acknowledgments 6

OVERVIEW

Introduction 10
Story of the Acquisition 18
Installation and Display 33

EXAMINATION

Introduction 34
Technical 38
Canvas 42
Ground Layer 60
Paint 88
Coatings 108

CONSERVATION

Removal of Old Retouchings and Varnish 132
Filling Losses in the Paint Layer 138
Inpainting and Reintegration 140
Markings 156
Incisions and Other Primary Markings 156
Primary White Markings and Finger Dabs 170

SCIENTIFIC ANALYSIS

Cross Sections 178
XRF Data 380

Endnotes 478
Equipment and Materials 488
Copyright 489

Foreword

The story of the *Crucifixion of Saint Andrew* (1606–7), the Cleveland Museum of Art's masterpiece by Michelangelo Merisi da Caravaggio, is one of timing, expertise, and a bit of intrigue. Out of view for more than three centuries, the painting surfaced in Spain in the early 1970s with an uncertain attribution and debated subject matter. Acquired by the CMA in 1976 under the direction of Sherman E. Lee, the canvas itself, one of five by Caravaggio in the United States at the time, retained some secrets.

Even as subsequent scholarship cleared up its pedigree and the subject that it depicted, the painting itself lacked clarity and depth of color: "Its full aesthetic potential was significantly compromised by complications from a previous restoration," according to the CMA paintings conservator Dean Yoder, author of this technical study. Now more than ever before, technology enables us to construct new narratives—or fill in narrative holes—about how works of art are conceived, made, revised, stored, transported, and previously cleaned and conserved. Joining the X-ray in the science of art is a plethora of imaging technology that helps conservators take a deep dive into the life of a work of art: infrared reflectography (IR), ultraviolet illumination (UV), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), X-ray fluorescence spectrometry (XRF), Fourier-transform infrared spectroscopy (FTIR), and Raman spectroscopy, all of which were used in the CMA's recent technical analysis and conservation of *Caravaggio's*

Raman spectroscopy, all of which were used in the CMA's recent technical analysis and conservation of *Caravaggio's Crucifixion of Saint Andrew.*

After carefully examining the conservation records, similar Caravaggio paintings in Europe, and the painting itself, Yoder embarked on a more than two-year cleaning and restoration project. Yoder's extensive work on the painting (logging over two thousand hours) not only revealed a ravishing new picture; he also uncovered a previously indiscernible figure in the shadows, realized surprising changes in its overall dimensions, and made important discoveries about Caravaggio's preparatory method of using incisions to "draw" on the canvas.

In 2014, for the first time ever at the museum, our conservation work was conducted in public as a Focus exhibition and work in progress. Visitors watched as Yoder painstakingly cleaned tiny portions of the Caravaggio in the exhibition space. Video, didactic panels, and life-size X-ray and IR images provided fascinating and unusual viewing for visitors.

Documenting every small step of the process, Yoder has produced a wealth of information regarding this particular painting, as well as details that will help advance future Caravaggio scholarship. This interactive digital publication is also a first for the museum, one of more to come.

William M. Griswold
Director
The Cleveland Museum of Art

Acknowledgments

The following people and institutions helped bring this multifaceted project to completion.

At the Cleveland Museum of Art, colleagues across disciplines offered support and assistance. I owe my deepest gratitude to Cory Korkow, associate curator of European art, for her constant encouragement and expertise in all matters relating to this project. Chief photographer Howard Agriesti and associate photographer and digital imaging technician David Brichford provided support and advice. Many colleagues in the conservation department deserve special mention: Per Knutås, chief conservator, and Marcia Steele, senior conservator of paintings, for their astute observations and support; Robin Hanson, associate textile conservator, for her help with the canvas weave structure; Joan Neubecker, conservation photographer, for her work stitching together X-rays and UV images; and Dave Piurek, technician for paintings and frames, for his assistance throughout the project. This publication came to fruition under editor Amy Sparks's watchful eye and through Tom Barnard's design mastery.

For his boundless energy and enthusiasm for this project, I'd like to especially thank CMA director William M. Griswold.

I am greatly indebted to Dr. Gregory Smith, senior conservation scientist at the Indianapolis Museum of Art, who over the years willingly accommodated the research needs of this project while running his own very busy

I am greatly indebted to Dr. Gregory Smith, senior conservation scientist at the Indianapolis Museum of Art, who over the years willingly accommodated the research needs of this project while running his own very busy laboratory.

Jiuan-Jiuan Chen and James Hamm, from Buffalo State College's Art Conservation Program, provided insight into UV imaging and Griffin varnish.

Numerous colleagues were generous with their time, providing technical images and sharing ideas about Caravaggio's painting technique: paintings conservators Ina Slama at the Kunsthistorisches Museum (KHM); retired KHM curator Wolfgang Prohaska; and Robert Wald—now head conservator of the Liechtenstein, the Princely Collections, Vienna—who conserved the *Crowning with Thorns* at the KHM. In Italy Dr. Roberta Lapucci, Caravaggio scholar, professor, and conservator in Florence, graciously shared her knowledge of his painting technique, made arrangements for us to visit the Roberto Longhi Foundation, and set up a meeting for us with the renowned art historian Dr. Mina Gregori. At the Museo di Capodimonte in Naples, Cory and I had the opportunity to meet with paintings conservator Angela Cerasuolo, who shared technical information about the *Flagellation*, painted in Naples during the same period as the *Crucifixion of Saint Andrew*. While in Naples, conservator and art historian Carmine Romano kindly arranged visits to see the *Seven Acts of Mercy* at the Pio Monte della Misericordia and the *Martyrdom of Saint Ursula* in the Galleria di Palazzo Zevallos Stigliano. Additionally, Giammarco Cappuzzo's information about the Back-Vega

in the Galleria di Palazzo Zevallos Stigliano. Additionally, Giammarco Cappuzzo's information about the Back-Vega conservation was instrumental in interpreting lost passages of our painting.

Furthermore, access to technical details about other masterpieces by Caravaggio was crucial in this study, and I turned to a number of conservators for information, data, and images: Alfred Ackerman, former paintings conservator at the Detroit Institute of Arts (*Martha and Mary Magdalene*); Claire Barry, paintings conservator at the Kimbell Art Museum (*Cardsharps*); and Scott Heffley, paintings conservator at the Nelson-Atkins Museum (*John the Baptist*). At the National Gallery in London, I'd like to thank Larry Keith, director of conservation, and Letizia Treves, curator of Italian and Spanish paintings 1600–1800, for sharing their insights about the Caravaggio paintings in their collection.

At the Metropolitan Museum of Art, New York, Dorothy Mahon, paintings conservator, advised on varnishing, and Keith Christiansen, curator and chair of European paintings, offered perceptive comments while I was treating the painting. I also owe thanks to Frank Zuccari, Art Institute of Chicago, for insight into the problems of poor saturation of varnish in old master paintings, and to Chris Stavroudis, paintings conservator in private practice in Los Angeles, for advice with cleaning systems.

Special thanks is due to Erin Benay, the Climo Assistant Professor of Renaissance and Baroque art at Case Western Reserve University; during the past few years, she shared with me her art historical insights on the *Crucifixion of Saint Andrew* and engaged with me in many thought-provoking

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Finally, the Cleveland Museum of Art is grateful to the Lubrizol Foundation for providing financial support to fabricate the microscope table in the exhibition *Conserving Caravaggio* in 2014. Also, framing and conservation made possible in part through the generosity of Diann G. and Victor J. Scaravilli.

Dean Yoder
Conservator of Paintings
The Cleveland Museum of Art

Introduction

Since the Cleveland Museum of Art acquired Caravaggio's *Crucifixion of Saint Andrew* in 1976, a tremendous amount of scientific research on the artist's work has produced a wealth of technical data, thus providing a more coherent framework of his materials and working process. This publication intends to add to that body of knowledge.

The Crucifixion of Saint Andrew was identified as a candidate for an extensive conservation treatment soon after it was acquired **FIG. 1**. The museum's then chief conservator Ross Merrill speculated that certain passages lacked legibility due to a problematic varnish, which over the decades continued to deteriorate. In 2013 a thorough evaluation confirmed the painting's exact state of preservation and provided a detailed account of what conservation could reasonably achieve.

While the primary reason for this conservation treatment was to address critical aesthetic issues related to the previous restoration, the opportunity to conduct the first in-depth technical analysis of the painting was equally important. The following pages provide a detailed account of the painting's condition before treatment and an investigation of Caravaggio's painting technique specific to the *Crucifixion of Saint Andrew* as revealed through the conservation treatment and technical imaging. Also presented here is the recent scientific analysis of the ground and paint layers conducted in collaboration with

Fig 1
Before treatment. *The Crucifixion of Saint Andrew*, 1606–7. Michelangelo Merisi da Caravaggio (Italian, 1571–1610). Oil on canvas; 202.5 x 152.7 cm. The Cleveland Museum of Art, Leonard C. Hanna Jr. Fund, 1976.2. Photo: Howard Agriesti

Gregory D. Smith, PhD, Otto N. Frenzel III Senior Conservation Scientist at the Indianapolis Museum of Art.

Confirming the painting's importance to the CMA collection, its conservation needs were the subject of a 2014 exhibition in the museum's Julia and Larry Pollock Focus Gallery, where visitors were able to witness the painting being cleaned and to ask questions about the conservation process. The first of its kind in the museum's history, this public conservation exhibition provided a detailed explanation of the painting's condition and construction through interactive video interviews, didactic panels, and full-scale X-ray and infrared (IR) backlit transparencies **FIG. 2**. After three months, the painting returned to the lab for the remaining conservation treatment. The project was completed twenty-one months later in May 2016.

Fig 2
Author and CMA paintings conservator Dean Yoder working in the exhibition *Conserving Caravaggio* at the Cleveland Museum of Art, 2014. Photo: David Brichford

Before starting this complex conservation project, learning as much as possible about the scope of the artist's work and surrounding preservation issues was essential. Accompanied by CMA associate curator of European art Cory Korkow, I traveled to Florence, Rome, and Naples to see many of Caravaggio's most important works, several of which had been recently conserved. We met with conservators, curators, and scholars who were generous with their time, experience, and in-depth knowledge.

These research trips were indispensable to the conservation process, allowing comparisons of both condition and painting techniques in the CMA painting with

other Caravaggio masterpieces. Understanding how common threads running through the artist's work relate to the CMA painting provided a conceptual framework for critical decisions, and helped target realistic and manageable aesthetic goals for the conservation treatment.

For example, Caravaggio's *Crowning with Thorns* (1603) in the Kunsthistorisches Museum in Vienna was a particularly important case study **FIG. 3**. Portrayed in rich black armor and a plumed hat, the soldier in that painting bears a striking resemblance to the soldier in the *Crucifixion of Saint Andrew,* except his pose is reversed and he faces downward. Long ago, key passages in the armor, hat, and plume of the soldier in the CMA painting sustained a significant amount of damage from an aggressive cleaning. These vulnerable paint layers had eroded to such an extent that previous restorers resorted to overpainting. These same passages in the armor in *Crowning with Thorns* are extraordinarily well preserved, revealing a beautifully nuanced paint structure in which the underlayers play an important role in the appearance of the figures. Studying firsthand how Caravaggio exploited and revealed his underlying paint provided a benchmark for interpreting how similar passages of the armor likely originally appeared in the CMA painting.

Conservation issues of the CMA painting were not unlike those in many other Caravaggio paintings and early seventeenth-century European works. There were abrasions to paint layers from prior cleanings, extensive repairs to

Fig 3
Crowning with Thorns, 1602–3. Caravaggio. Oil on canvas; 138 x 173 cm. Kunsthistorisches Museum, Vienna. Photo: Nimatallah / Art Resource, NY

multiple tears and holes in the canvas, passages of heavy retouching used to cover the damages, and cracked, discolored varnish layers over top. While the responsibility of conserving such a famous masterpiece carried additional weight, all of the problems had relatively simple solutions once they were broken down into individual parts. When approaching complex treatments that can take years of work, every step requires focus and dedication to achieve the high level of finish that the artwork demands.

A conservation project such as this, involving more than a year of reconstructive inpainting, is by its nature an interpretive exercise. Each conservator brings a unique experiential understanding of how a painting, or any work of art, should appear when the treatment is complete. The overriding concept for this particular conservation treatment was to accept all of the effects of age, including cracking and increased transparency in the paint, but also to visually subtract the negative effects of damage caused by tears and overcleaning. The particular reconstructive techniques used to achieve this goal are outlined in the Conservation section.

Conservators also bring a contemplative perspective to the process, knowing that seventy-five to one hundred years later a new intervention will likely be required to correct the inevitable degradation of their materials. All conservation materials and processes must be reversible well into the future to ensure the painting's long-term preservation. Conservators are therefore always limited by the materials and technology of their time.

Story of the Acquisition

Caravaggio's *Crucifixion of Saint Andrew* was missing for more than three centuries. However, three copies were known to exist in Europe: the so-called Back-Vega painting in Vienna, now in the Spier Collection in London **FIG. 4**; the painting in the Musée des Beaux-Arts de Dijon **FIG. 5**; and the painting in the Museo de Santa Cruz, Toledo **FIG. 6**.[1] Together they display a broad range of quality and condition. Heavily damaged during the Spanish Civil War, the Toledo version is the most dissimilar of the copies; its expanded verticality stretches the composition. The Dijon and Back-Vega paintings are in better overall condition than the Toledo copy and are more similar in size to the CMA painting.

According to Giovanni Bellori (1613–1696), Caravaggio's earliest biographer, Juan Alonso Pimentel y Herrera, count of Benavente and Spanish viceroy to Naples, commissioned the *Crucifixion of Saint Andrew* and transported it back to his native Spain in either 1607 or possibly 1610.[2] A little over forty years later, an inventory and appraisal after the death of the count's grandson in 1653 placed the painting at the family palace in Valladolid, Spain.[3] At that time the painting was listed as the most valuable artwork in the Benavente collection. Remarkably, its whereabouts remained unknown for the next 320 years, until 1973, when it was discovered in the collection of José Manuel Arnaiz.[4]

Fig 4
The Back-Vega version of the *Crucifixion of Saint Andrew* after a recent treatment. *Crucifixion of Saint Andrew* (copy after Caravaggio), 1608–10. Oil on canvas; 200 x 150 cm. Spier Collection, Brentwood Holdings Assets Ltd. Photo: Matthew Hollow

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Fig 5
The Crucifixion of Saint Andrew (copy after Caravaggio), c. 1607–15. Attributed to Louis Finson (Flemish, c. 1580–1617). Oil on canvas; 209 x 151.5 cm. Musée des Beaux-Arts de Dijon, inv. 5008. © Musée des Beaux-Arts de Dijon / François Jay

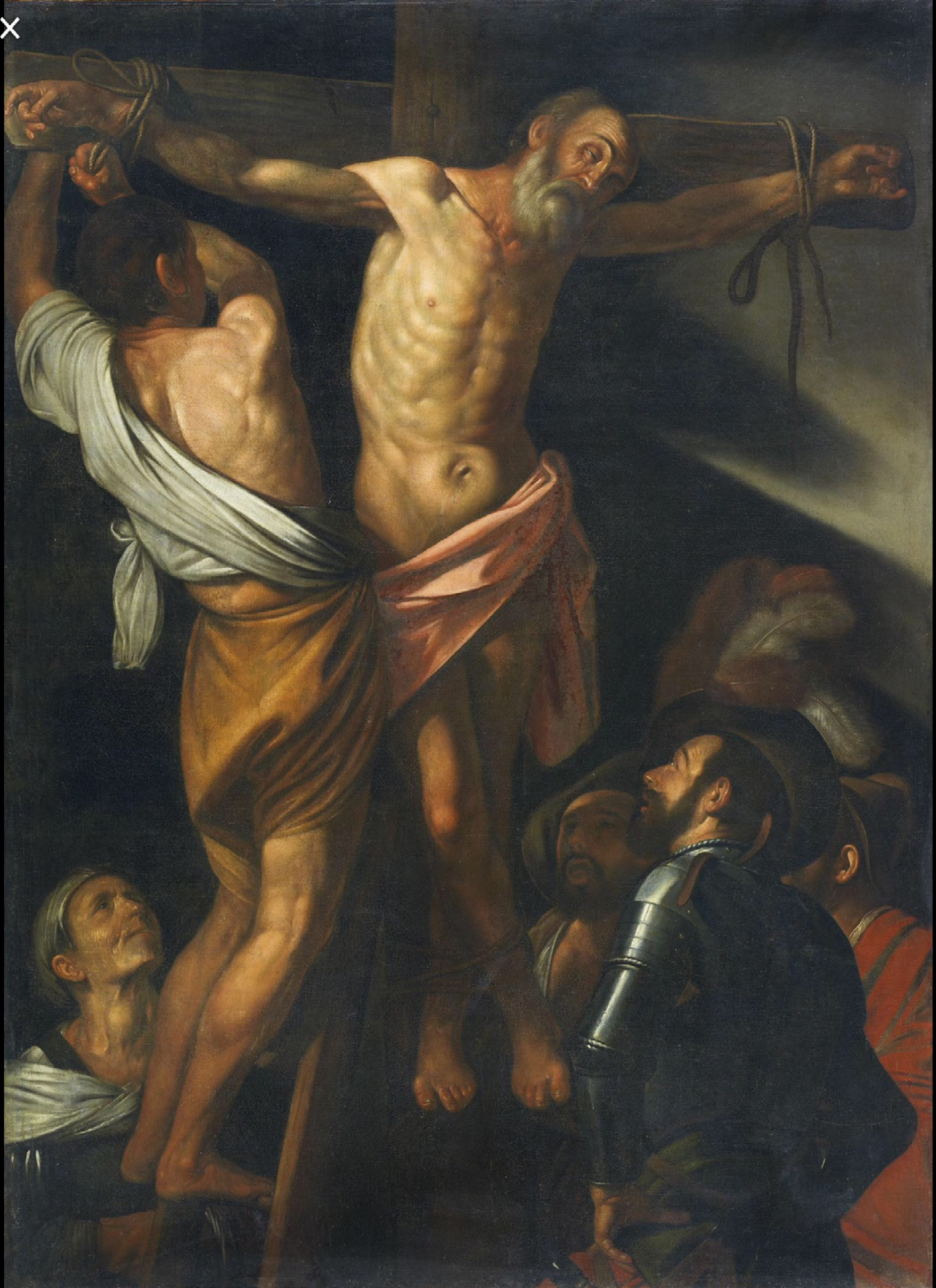

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Fig 6
The Crucifixion of Saint Andrew (copy after Caravaggio), c. 1610–20. Jusepe de Ribera (Spanish, c. 1591–1652). Oil on canvas; 232.5 x 160 cm. Museo de Santa Cruz, Toledo, Spain. Ministerio de Educación, Cultura y Deporte. © José Baztàn

In the fall of 1973, Alfonso E. Peréz Sánchez included the painting in his exhibition *Caravaggio y naturalismo español* in Seville. Peréz Sánchez, however, was hesitant to attribute the painting to Caravaggio, mainly because Saint Andrew was not depicted on an X-shaped cross, or *crux decussata*—the type of cross normally associated with the saint, at least since the mid-fifteenth century.[5] Also, the inventory from February 20, 1653, stated that there were only three executioners in the painting. However, in the newly discovered painting there were four: the figure on the ladder and the group of three in the lower right. These two inconsistencies led Peréz Sánchez to propose that the main figure was perhaps Saint Philip, instead of Saint Andrew. A small label on the reverse of the painting provides unique documentation for Peréz Sánchez's theory; it has question marks after both Caravaggio and Saint Philip, a theory also presented in the exhibition catalogue.[6] After the exhibition, however, the painting's owner, José Arnaiz, discovered a brief notation in an earlier inventory reference from January 3, 1653, stating that three executioners were located in the lower right of the painting, thus clarifying the discrepancy.[7]

Arnaiz made an X-ray of the painting in his Instituto Técnico in Madrid in the early 1970s.[8] The X-rays revealed prominent artistic changes or *pentimenti* in the placement of the elderly woman's hands and the soldier's profile. This important discovery indicated the painting was likely an original creation; artist's changes to a composition are rarely present in copies. Peréz Sánchez was aware of the

pentimenti but nevertheless remained skeptical that the canvas was by Caravaggio. At the time, it may have been difficult to see past the poor quality of the former restoration. Black-and-white photographs reveal a rather crude, cartoonish reconstruction of the soldier's damaged eye. Another detail of the raised arm of the executioner on the ladder shows a sizable area of damage.

The year following the painting's discovery, art historian and Caravaggio scholar Benedict Nicolson wrote that while he did not think it was in poor condition, it was in need of cleaning.[9] The term *cleaning*, however, was often used loosely at that time to indicate removal and replacement of an entire restoration. Consequently, toward the end of 1974 the Swiss restorer Jan Dik performed an extensive restoration treatment in consultation with two renowned Caravaggio scholars, Luigi Salerno and Denis Mahon.[10]

A written account of the painting's condition before treatment does not exist; however, we can refer to small set of eight-by-ten-inch black-and-white photographs that Dik provided before treatment, after cleaning, and after treatment. These photographs confirm that the painting had received a significant amount of repainting to compensate for numerous tears and a slash through the soldier's eye. A detail of the executioner on the ladder before treatment reveals that the loss, accompanied by heavy abrasions, had a limited amount of retouching. A detail of the same area after treatment reveals that Dik significantly improved this area

with additional and more refined retouching. Dik's 1974 restoration greatly improved the painting's overall legibility. One of the most noticeable improvements was his sensitive reconstruction of the soldier's eye **FIGS. 7, 8.**

Any debate or confusion over which saint is portrayed was put to rest after Anne Tzeutschler Lurie and Denis Mahon published their seminal article, *"Caravaggio's Crucifixion of Saint Andrew* from Valladolid," in January 1977.[11] Deciphering the painting's iconography, Lurie and Mahon explained that over the centuries the crux decussata associated with Saint Andrew came from a translation error; it was even a topic of debate among prominent theologians at the turn of the seventeenth century.[12]

Fig 7
The soldier's eye and mouth before treatment, 1974

Lurie and Mahon wrote convincingly that the painting portrays the last moments of Saint Andrew's life as described in the *Golden Legend.* Andrew had been preaching in Patras, now modern Greece, when he baptized Maxilla, the wife of the Roman proconsul Aegeas, who responded by ordering Andrew's crucifixion. Bound with ropes to the cross to prolong his suffering, Andrew began to preach from the cross to a gathering crowd. By the third day, twenty thousand people demanded his release. Fearing an uprising and personal injury from the masses, Aegeas acquiesced to the pleas of the crowd. From the cross, Andrew prayed for his deliverance (death by martyrdom), insisting to Aegeas that he would not be taken down alive. The painting represents the quintessential moment when Andrew's prayers were answered: a bright light descends from the

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Fig 8
The soldier's eye and mouth after restoration by Jan Dik, 1974

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heavens to envelop him and paralyze the executioners, rendering them powerless to untie the ropes as Andrew passes away.[13]

With Dik's improvements and Lurie and Mahon's scholarship, the Cleveland Museum of Art, under the directorship of Sherman E. Lee, proceeded in 1976 with what became a landmark acquisition for the museum's permanent collection. The *Crucifixion of Saint Andrew* is one of only a handful of paintings by Caravaggio held in the United States, and arguably the only altarpiece.[14]

End Notes

1. The Back-Vega version was previously in the collection of Emmerich and Christa Back-Vega, who presented the work as the original version in 1954. It is now in the Spier Collection in London and considered by some to be a second autograph version by Caravaggio. See Gianni Papi, *Caravaggio: The Back-Vega Crucifixion of Saint Andrew* (Milan: Skira, 2016), 28.
2. The count sent a number of artworks back to Spain in 1607 then again in 1610 after completing his term in Naples. For an in-depth discussion of the painting's history and travels from Naples to Spain, see Erin E. Benay, *Exporting Caravaggio: The Crucifixion of Saint Andrew*, Cleveland Masterwork Series 4 (Cleveland: Cleveland Museum of Art; London: Giles, 2017).
3. There are two inventory documents from 1653: January 3 and February 20. The former mentions four executioners in the painting, while the later inventory indicates three.
4. For more information on Arnaiz see http://www.arnaiz.com/castel.htm.
5. Anne Tzeutschler Lurie and Denis Mahon, "Caravaggio's *Crucifixion of Saint Andrew* from Valladolid," *Bulletin of the Cleveland Museum of Art* 64, no. 1 (1977): 12–13.
6. Alfonso E. Pérez Sánchez, *Caravaggio y el naturalismo español*, exh. cat. (Madrid: Raycar, 1973), cat. no. 4.
7. Lurie and Mahon, 10.
8. José Manuel Arnaiz founded the Instituto Técnico de Expertización y Restauración de Madrid in 1973, specializing in developing techniques for technical research and conservation.
9. Benedict Nicolson, "Caravaggio and the Caravaggesques: Some Recent Research," *Burlington Magazine* 116 (October 1974): 608.

9. Benedict Nicolson, "Caravaggio and the Caravaggesques: Some Recent Research," *Burlington Magazine* 116 (October 1974): 608.
10. Salerno and Mahon had authenticated two Caravaggio paintings in American museums: *Martha and Mary Magdalene* (Detroit Institute of Arts) in the 1960s and *The Crucifixion of Saint Andrew* (Cleveland Museum of Art) in the 1970s. See https://dictionaryofarthistorians.org/salernol.htm.
11. Lurie and Mahon, 13–15.
12. Ibid., 13. Also, theologian Joannes Molanus's scholarly research published in 1594 stated that the crux decussata was in error. See Henricus Cuyckius, ed., *De historia SS. Imaginum et picturarum pro vero earum usu contra abusus* (Louvain, Belgium, 1594), bk. IV, chap. LI, fol. 162v.
13. Jacobus de Voragine, *The Golden Legend of Jacobus de Voragine*, trans. Granger Ryan and Helmut Ripperger (Salem, NH: Ayer, 1969), 12–13.
14. The Nelson-Atkins Museum of Art in Kansas City has argued that their Caravaggio painting, *Saint John the Baptist in the Wilderness* (1604–5), was intended as an altarpiece. However, Ottavio Costa, who commissioned the painting for the altar of the oratory dedicated to Saint John the Baptist in Coscente, kept the original and sent a copy. See Sebastian Schütze, *Caravaggio: The Complete Works* (Cologne: Taschen, 2009), 268.

Installation & Display

Analysis Before Conservation

The technical study described here was undertaken to resolve the aesthetic problems apparent when the painting entered the CMA collection. Even though Jan Dik's 1974 restoration had improved the painting's overall legibility by removing previous repainting, problems in the varnish were already present when the painting arrived in Cleveland. The CMA's then chief conservator Ross Merrill observed areas of bloom (a whitish haze) in the varnish and blanching (a splotchy, crusty opaque appearance) underneath the varnish, which he suspected was the incomplete removal of earlier varnish coatings. Merrill described the varnish as a "complex multilayered system" that filled the cracks and valleys of the cupped paint.[15] He further stated that the top varnish had been thickly brushed on, producing an extremely high gloss with brilliant specular reflections that reduced the ability to see into the darker colors.

Because Mahon had originally consulted with Dik during the restoration treatment, he traveled to Switzerland with a questionnaire prepared by Merrill. If Merrill was to correct any problems associated with the varnish, he needed to know exactly what type of varnishing layer system and cleaning techniques Dik had used in his treatment. According to a Western Union Telegram in the conservation files, which preceded Mahon's return with the more detailed questionnaire, the bloom was removable by rubbing the surface with an antielectrostatic cloth.

In the questionnaire Dik confirmed Merrill's initial observations that the varnish was indeed a complex multilayered system, though Merrill noted that rubbing the surface to remove the varnish bloom, as instructed in the telegram, was ineffective. He did discover that an application of "strong organic solvents or reagents" over the varnish was capable of visually reversing the underlying blanching, but predicted that this remedy would not be long lasting. As an alternative, Merrill attempted to reverse the bloom by spraying a solvent (xylene) over the painting to reform the varnish.[16] This appears to have temporarily solved the problem of the surface bloom, though over the years, bloom continued to recur over the varnish layer and was routinely reduced by buffing with a soft cloth.

Merrill's report is remarkably relevant to the present study, because it indicated that the aesthetic problems related to the varnish have existed since the acquisition, and that more in-depth study was needed to determine exactly what materials were present over the paint surface. Equally essential was the identification of the original materials used in the creation of the painting as well as those materials from restorations that occurred before the 1974 treatment. Understanding how both original and restoration materials interact with each other would also help provide answers to many of the painting's lingering aesthetic issues and supply concrete information for choosing the best course of treatment for long-term preservation.

15. Ross Merrill, “Construction and Condition Report,” February 17, 1976, Cleveland Museum of Art conservation files.
16. “Statement by Jan Dik on His Restoration of Caravaggio’s ‘Martyrdom of St. Andrew,’” March 20, 1976, CMA conservation files. There is no mention of the outcome of this treatment.

Technical Imaging

X-radiography

X-rays lie in the region of electromagnetic radiation with very short wavelengths beyond the ultraviolet region. This type of radiant energy can penetrate materials to varying degrees depending on their density and composition. X-ray imaging provides information about a painting's structural integrity, revealing underlying canvas and paint structures, artist's changes, distribution of heavy metal pigments, and insight into an artist's painting techniques. An assessment of a painting's condition often begins with an X-ray, much like visiting a doctor. Structural damages covered by restoration are often immediately identified, providing clues to a painting's history.

X-radiograph mosaic

Infrared Reflectography (IRR)

Developed by Dutch physicist J.R. J. van Asperen De Boer in the late 1960s, infrared reflectography (IRR) is a photographic method used to see through upper paint layers. Invisible to the human eye, the longer wavelengths in the infrared region are detectable with special cameras and can provide critical information about a painting's structure, revealing underlying pigments and drawing, artistic changes, and structural damages covered by restoration. Like X-rays, IRR has become a standard imaging technique for study in conservation.

Technical Imaging

X-radiography

X-rays lie in the region of electromagnetic radiation with very short wavelengths beyond the ultraviolet region. This type of radiant energy can penetrate materials to varying degrees depending on their density and composition. X-ray imaging provides information about a painting's structural integrity, revealing underlying canvas and paint structures, artist's changes, distribution of heavy metal pigments, and insight into an artist's painting techniques. An assessment of a painting's condition often begins with an X-ray, much like visiting a doctor. Structural damages covered by restoration are often immediately identified, providing clues to a painting's history.

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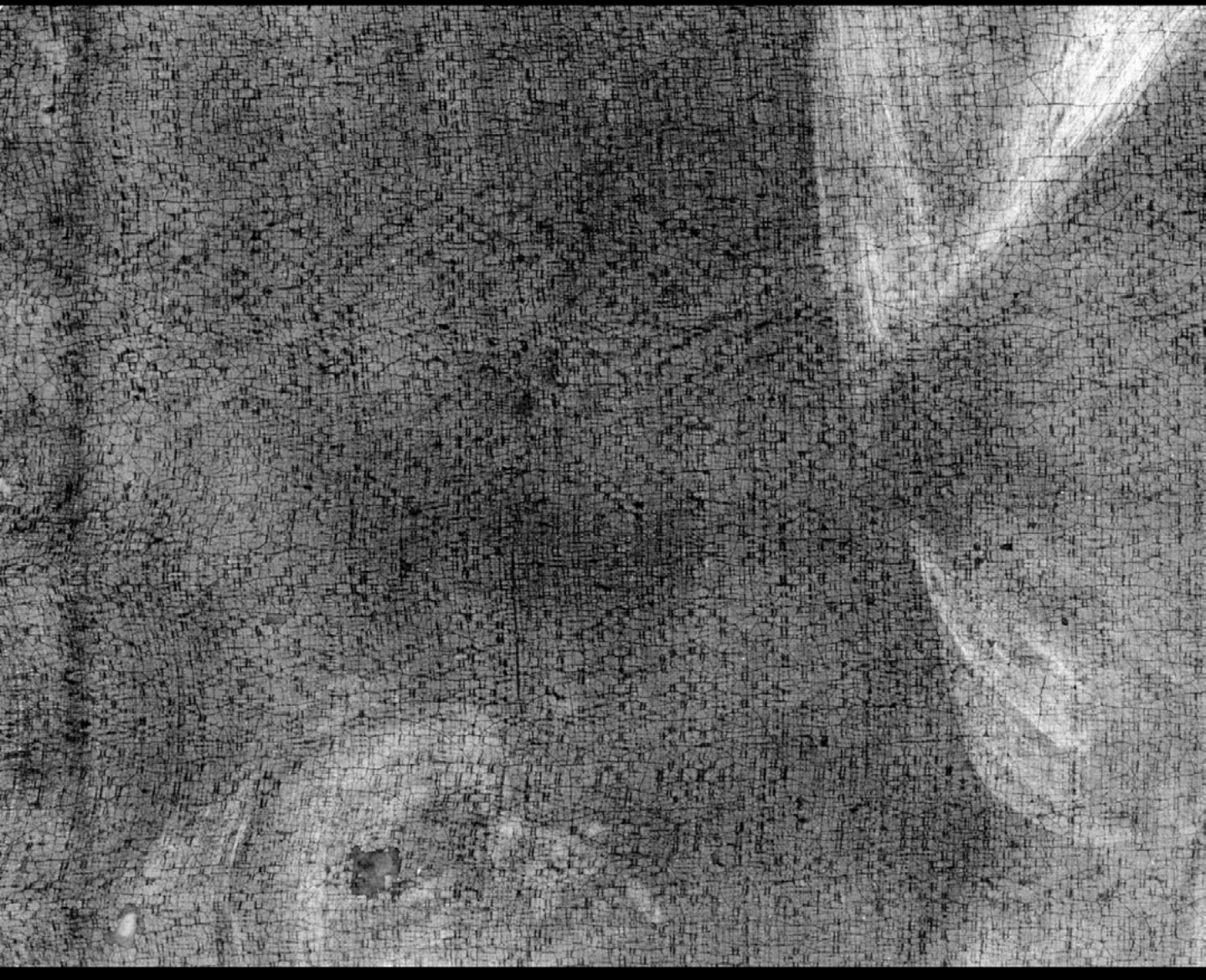
Support: Construction and Condition of the Original Canvas

For the primary support of the *Crucifixion of Saint Andrew*, Caravaggio used a large single piece of patterned linen canvas with a warp-float weave in which pairs of warp threads span weft threads and are interlaced within a plain weave to create an overall repeating diamond pattern **FIG. 9.**[17] According to textile expert, Irene Emery this weave structure, characteristic of damask, or more specifically, huckaback, was particularly useful for toweling due to the absorbency created by the raised warp threads.[18] While simple plain-woven canvases were most common for painted supports, examples of self-patterned fabrics, such as diamond-weave or twill lozenge variants,[19] are well documented throughout the sixteenth and seventeenth centuries in Italy and Spain.[20] In Italy, diamond-patterned fabrics are often referred to as Flemish damask-weave or *tovagliato di Fiandra*.[21] One of the great benefits of these patterned fabrics, or tablecloth linens as they are often called, was their availability in wider widths and heavier thread densities, making them suitable for larger-scale paintings and altarpieces.[22] Coincidentally, another important masterpiece in the Cleveland Museum's collection, *Christ and the Virgin in the House at Nazareth* (c. 1640) by Francisco de Zurbarán (Spanish, 1598–1664), was also painted on a single piece of diamond-weave canvas.[23]

Fig 9
X-ray of the canvas weave showing repeating diamond pattern

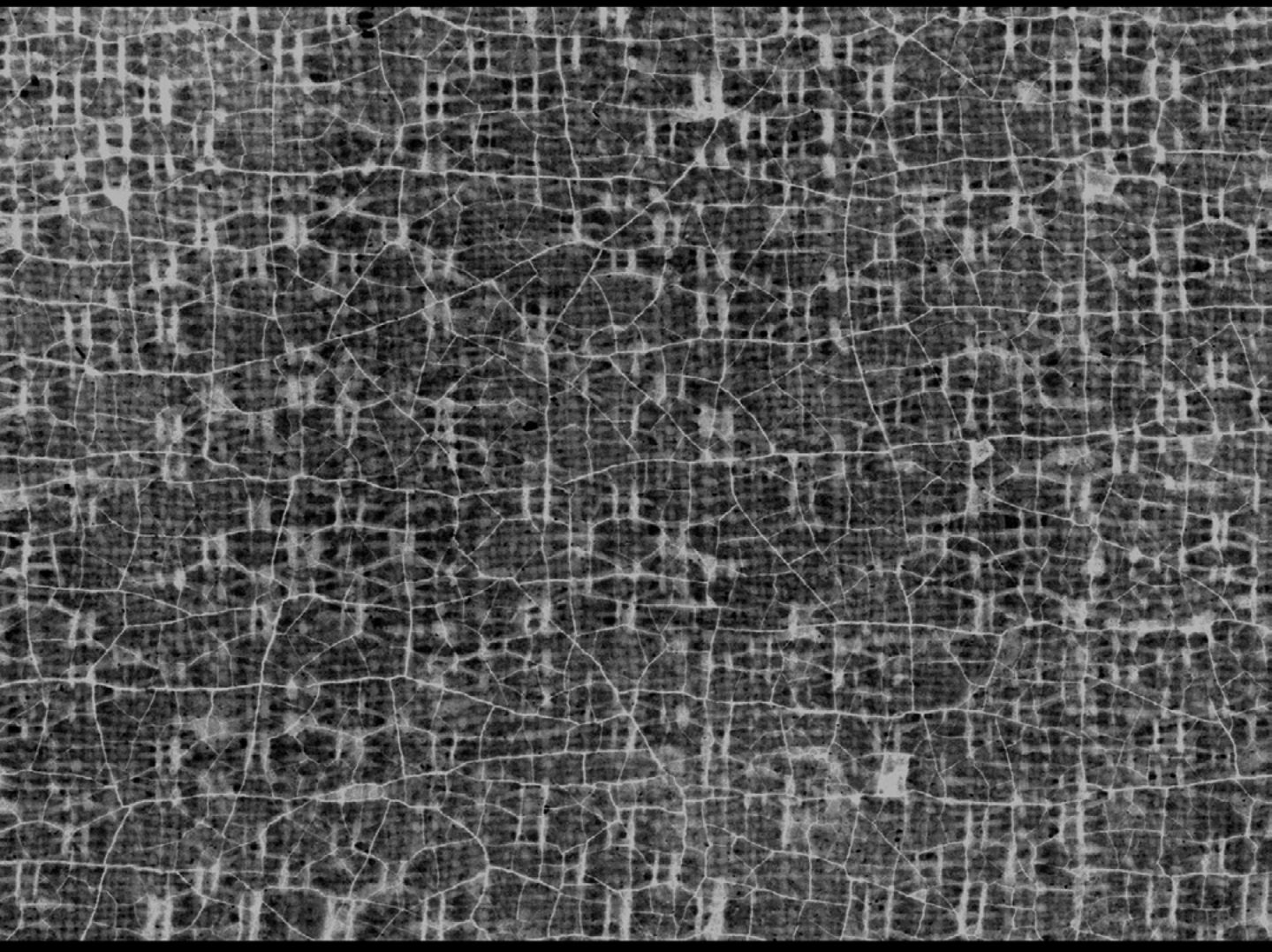


Caravaggio used a patterned-weave canvas for only two other paintings: *The Rest on the Flight into Egypt* (1595), now in the Museo Doria Pamphilj in Rome, and *Bacchus* (1596–97), now in the Uffizi Gallery in Florence.[24] Both were executed during his time in Rome (1592?–1606), though in the case of the *Flight into Egypt*, Caravaggio painted on top of a preexisting painting, so we might assume that the recycled canvas was chosen for its convenience as a readymade support, having nothing to do with its weave structure.

Because a lining fabric covers the reverse of the *Crucifixion of Saint Andrew*, using an X-ray image was the most practical method to establish an accurate thread count for the canvas. The thin, even applications of mostly radio-transparent (transparent in X-rays) paint in the background area just above the elderly woman in the lower left yielded an ideal location to study the weave structure. Developed X-ray film from this area was placed over a light box and photographed with a digital camera, then inverted in Photoshop to produce an X-ray positive. The X-ray positive provided a far more readable image to determine the thread count: fourteen threads per centimeter in both warp and weft directions **FIG. 10**. The same thread count was then verified on the actual X-ray film under magnification.

Fig 10
X-ray positive image of the canvas weave structure in the area above the elderly woman's head

All of the X-ray films were then digitized and assembled in Photoshop to produce a seamless X-ray composite.[25] The composite revealed pronounced cusping, a pattern of wavy distortions, along the right and left outside edges caused by the initial stretching of the canvas, and only a slight amount

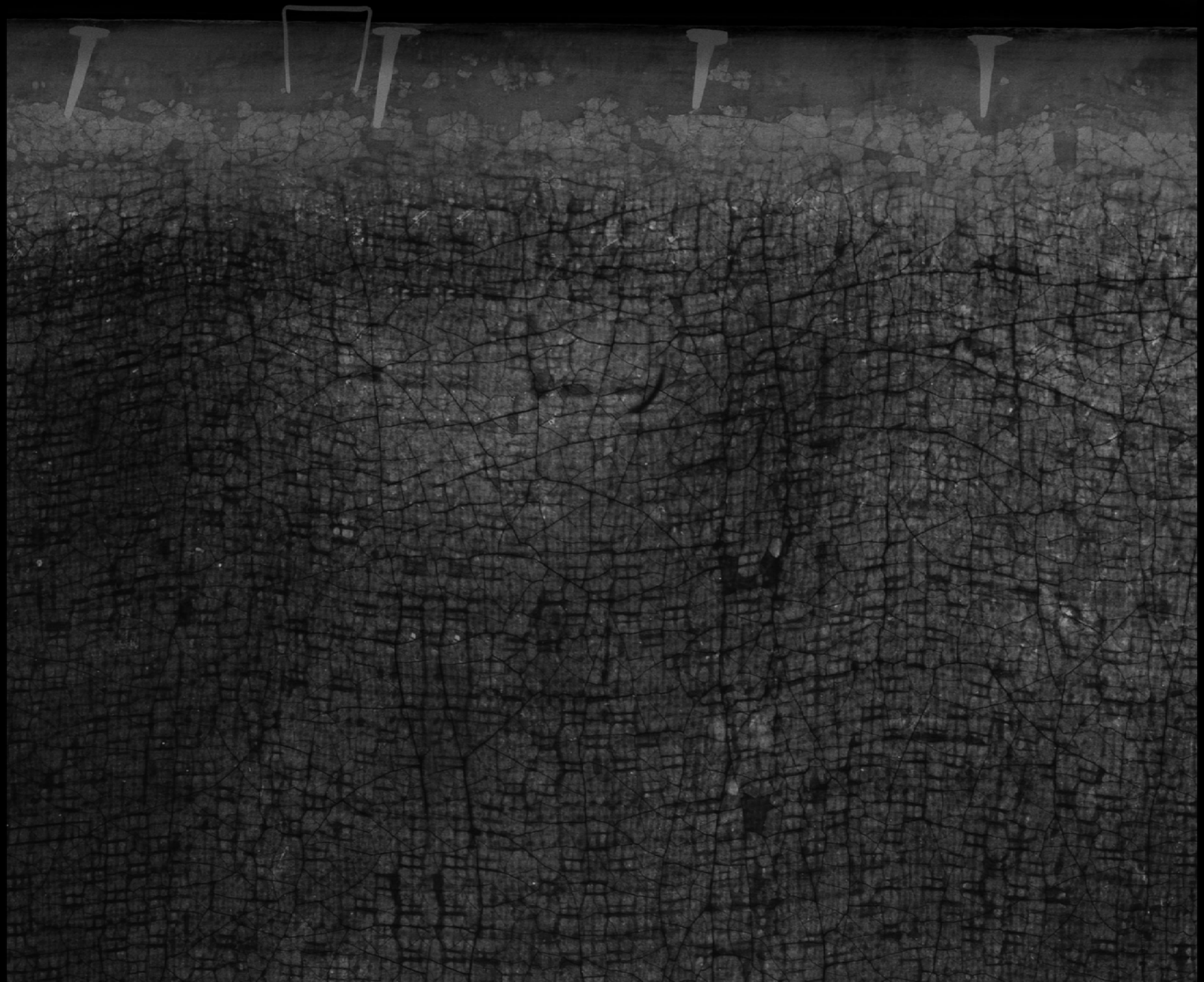


of cusping at the top and bottom. Because stretching distortions in a canvas lock into place after the application of the sizing and ground layers, the amount of cusping illustrates not only the uniformity of this stretching, but also the stretching properties of this particular canvas. Along the side edges, termination points of cusping present in the original canvas reveal that the painting's current width is very close to its original dimension, likely within a few centimeters. At the time of the acquisition, Merrill suggested that the lack of cusping along the top and bottom edges might indicate that the painting's height had been reduced.[26] However, this assertion is difficult to prove for a couple reasons: first, the stretching properties of canvases can vary greatly according to weave structure,[27] and second, it is possible the artist trimmed the canvas in the vertical direction after applying the ground.

Fig 11
X-ray of a tattered edge

Further complicating the question of trimming, there is clear evidence around the entire perimeter that at some point in the past a portion of the original painting was turned over and used as a tacking edge. This was first observed in the X-ray composite and later confirmed after cleaning. Here, the X-ray composite clearly reveals a tattered canvas edge with regularly spaced holes where tacks once held the canvas in place over a smaller stretcher **FIG. 11**. Fortunately, an earlier structural treatment had the sensitivity to unfold and reincorporate the damaged edges into the overall format.

Another clue that the vertical dimensions of the



Cleveland painting were reduced may be found by referring to both the Dijon and Toledo copies.[28] The Back-Vega version is less reliable in this regard, since it was trimmed along the top, left, and bottom edges.[29] In the lower right, the distance from the top of the soldier's sword (pommel) to the bottom edge in the Cleveland painting is nearly the same as in the Dijon painting, while the Toledo copy exposes slightly more of the sword below the pommel. Therefore, based on visual evidence of two of the three copies, it seems likely that the bottom edge of the Cleveland painting may be fairly close to how it was originally painted, possibly within a few centimeters. Trimming that might have occurred along the top edge of the Cleveland painting may be best determined by comparison with the Dijon copy. The latter shows slightly more space between the top of the cross's transept to the top of the painting, suggesting a slight amount of trimming along the top edge of the Cleveland painting, perhaps four to five centimeters. The Toledo copy seems less reliable when comparing the amount of space at the top, because the composition was intentionally elongated from the bottom up by the artist/copyist. And as previously mentioned, the significant trimming of the Back-Vega along this edge inhibits any kind of meaningful comparison.

Another possibility is that the artist himself could have trimmed the painting from a larger working strainer frame. This would allow for some flexibility before finalizing the exact placement of the edges. There is evidence that Caravaggio repositioned the edges of the *Seven Acts of Mercy*[30]

and slightly expanded the edges of the *Flagellation*,[31] both painted during the artist's first visit to Naples in 1606–7, the accepted date of the *Crucifixion of Saint Andrew*.

Original Canvas: Condition

With a better understanding of the structure of the original canvas, its condition can be evaluated. X-rays clearly reveal tattered and torn edges around the original canvas. As previously mentioned, regularly spaced holes and a straight line of paint losses around the entire perimeter reveal that the painting was made smaller at one time in its history. The most recent lining, executed perhaps one hundred to one hundred and fifty years ago (based on the amount of oxidation of the lining fabric), reincorporated the damaged original perimeter back into the picture plane. However, instead of carefully reconstructing the areas of loss around the perimeter, the last two interventions painted over areas of intact original paint with an arbitrarily conceived one-inch-wide painted brown stripe to cover the heaviest damage **FIG. 12**. This was likely done to expedite the extensive retouching that otherwise would have been required.

Fig 12
Lower right corner showing the brown stripe

The lining also stabilized the complex tears in the upper left, running through the head, arm, and draped white clothing of the executioner standing on the ladder; in the lower left, tears through the elderly woman's neck and shawl lower left, tears through the elderly woman's neck and shawl; and in the lower right, complex tears in the armor of

the top of the paste adhesive that was spread out over the lining fabric. The two canvases are then fused together with warm irons that slowly drive out the moisture. The success of paste linings depends on experience and skill found in each tradition; inexperienced hands can result in disastrous effects, as the heat and weight of the irons in combination with moisture from the paste can soften and flatten the impasto in the paint layer. The application of paste linings by highly skilled specialists remains fairly common in some European countries. In the United States, however, the practice has now been almost entirely replaced by reversible adhesives and heated lining tables designed to reduce problems associated with elevated amounts of moisture from paste adhesives.

Fig 14
Reverse of the painting

The Crucifixion of Saint Andrew was hand lined with a traditional paste adhesive (containing hide glue and starch) to a medium-weight, plain-woven linen canvas. After lining, the painting was stretched over a five-member, heavyweight, pine wood, simple-mortised, keyable stretcher (one inch deep and four and three-quarters inches wide) with closed bridle joints,[33] corner miters, and rounded keys **FIG. 14**. The shoulder of the closed bridle was located at the top and bottom stretcher members, producing a more stable substrate for tacking along the outside edge. Judging from the amount of oxidation present in the wood, the stretcher was likely the same age as the lining. Tacking edges from the lining canvas were firmly glued to the outside edges of the stretcher with strong hide glue. Excess lining canvas was

trimmed flush with the back edge of the stretcher along the top and left. On the right and bottom edges, about one inch of excess tacking margin fabric was folded over and glued to the stretcher's back edge. Moderately sized, slightly oxidized iron tacks also secured the lining canvas to the stretcher.

Presently, the lining canvas displays only minor signs of deterioration caused by oxidation, and appears to be well adhered to the original canvas. There had been some discussion of removing the glue lining at the time of acquisition because it was thought to be contributing to the extensive cracking and creating instability in the paint layer.[34] Over the past fifty years, however, conservators have become less inclined to subject paintings to the severe stress of a paste lining removal, which involves the use of scalpels to mechanically scrape away the adhesive residues from the reverse of the canvas once the lining canvas is removed. In the case of this particular canvas, the adhesive would likely be trapped underneath the floating warp threads, and continuous scraping could easily compromise the structural integrity of the original canvas. Moist poultices are often used to slowly swell and soften the paste to improve and accelerate its removal. However, in this case moisture would inevitably penetrate through the back of the original canvas and swell the binder in the lower ground layer.

Even though by its nature the paste lining adhesive is reactive to humidity, and eventually may require removal, it may actually be fairly compatible with the original canvas and the composition of the first ground layer (discussed in

the next section), as long as temperature and humidity remain stable. This is a good example of why museums spend a great deal of effort and expense to provide stable environments for fragile works of art otherwise negatively impacted by rapid changes and extremes in temperature and humidity.

17. Canvas fibers from the original support, examined with a polarized light microscope at the Cleveland Museum of Art, exhibit characteristics consistent with bast fibers, most likely linen.
18. Irene Emery, *The Primary Structures of Fabrics* (London: Thames and Hudson, 1994), 125–26. The English word *huckaback* may derive from traveling hucksters who peddled linens in the British Isles.
19. Ibid., 98. Diamond (or lozenge) twill patterns where both horizontal and vertical reversals of diagonals are evenly spaced and correlated, whether or not they create symmetrical diamond figures.
20. Marco Ciatti and Brunetto Brunetti, ed., *Caravaggio's Painting Technique: Proceedings of the CHARISMA Workshop* (Florence: Nardini Editore, 2012). See especially Claudio Seccaroni, "A New Survey of Caravaggio's Canvases and Preparatory Layers: Materials and Aesthetic Effects," 60.
21. Rossella Vodret, *Caravaggio: Works in Rome; Technique and Style* (Milan: Silvana, 2016), 1:23.
22. For an extensive survey of patterned fabrics see Seccaroni, "New Survey of Caravaggio's Canvases," 61.
23. Oil on canvas, 165 x 218.2 cm; Leonard C. Hanna Jr. Fund, 1960.117. For more information about the canvas weave, see Zahira Véliz, "A Painter's Technique: Zurbarán's *The Holy House of Nazareth*," *Bulletin of the Cleveland Museum of Art* 68, no. 8 (1981): 271–85.
24. Merrill's conservation report refers to Edoardo Arslan, *Nota Caravaggesca, Arte Antica e Moderna* 6 (April/June 1959): 212, figs. 1 and 2, where *Bacchus* is described as having a "complex diamonded-patterned fabric (five small diamonds within a larger diamond, which has four diamonds within a

diamond at the intersections of the larger pattern)." *The Rest on the Flight into Egypt* is painted on a support with an even more complex diamond design (five diamonds in a double cross within a diamond and four diamonds at the intersections of the larger diamond).

25. Twenty-eight X-ray films were inserted between the reverse of the lining canvas and stretcher bars, and exposed to 16 kilovolts (kV) and 3 milliamps (mA) for 210 seconds, the same exact settings used to produce the 1976 films. An additional eighteen films collected remaining X-ray information around the edges. The new X-rays were digitized and assembled in Photoshop to produce a seamless, high-resolution image. Individual X-rays were photographed on a light box using EquaLight™ software that compensates for possible uneven lighting, and then assembled manually in Photoshop.
26. Merrill, "Construction and Condition Report."
27. Preliminary stretching tests on modern plain-weave linen in the CMA conservation lab conducted with Jennifer Brunton, Master of Letters candidate, Centre for Textile Conservation and Technical Art History, University of Glasgow, demonstrated that greater cusping in the weft can be produced after stretching, preshrinking, and sizing, or restretching after preshrinking. These same tests indicated that in both cases less cusping was always seen in the warp.
28. Compare the measurements of the four paintings: Cleveland Museum of Art, 202.5 x 152.7 cm; Musée des Beaux-Arts, Dijon, 209 x 151.5 cm; Museo de Santa Cruz, Toledo, 232.5 x 160 cm; Back-Vega version, 200 x 150 cm.
29. The conservator of the Back-Vega version, Bruno Arciprete, estimates that the painting may have been trimmed by 5 to 6 cm in width and 10 to 11 cm in height, and was once closer to the dimensions of the Cleveland painting. See Papi,

to the dimensions of the Cleveland painting. See Papi, *Caravaggio: The Back-Vega Crucifixion of Saint Andrew*, 46.

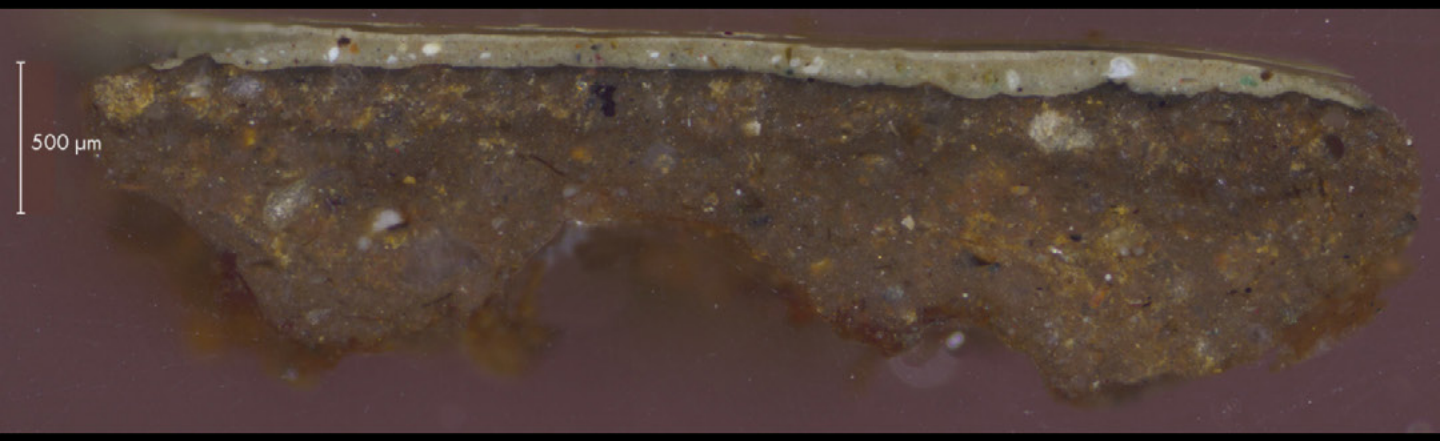
30. Seccaroni, "New Survey of Caravaggio's Canvases," 62.
31. Bruno Arciprete, "Il restauro," in *La Flagellazione di Caravaggio: Il restauro*, ed. Denise Maria Pagano (Naples: Electa, 2004), 32.
32. These canvas inserts, of a type commonly used to span large areas of loss in old restoration treatments, were originally coated with a lead white ground layer and thus are visible in the X-ray.
33. Mark Bockrath and Barbara Buckley, "Illustrated Historical and Original Stretchers and Strainers," in *Painting Conservation Catalog*, vol. 2, *Stretchers and Strainers*, comp. Barbara Buckley (Washington: Paintings Specialty Group of the American Institute for Conservation of Historic and Artistic Works, 2008), 89, illus. 22.
34. Merrill, "Construction and Condition Report."

Ground Layer: Construction and Condition

A ground layer, or priming layer, is typically used to prepare a canvas for painting. Usually the canvas is preshrunk before stretching, then sized by applying a thin, diluted layer of hide glue. The sizing prepares the fabric to receive the ground layer, preventing grounds with oil binders from penetrating through and rotting the canvas, or in the case of grounds with water-based binders, improving the bond with the canvas. The ground layer provides the foundation for the paint, its physical characteristics of color, texture, and absorbency affecting how the paint moves or glides over the surface. Based on these factors, ground formulations can be quite particular to the artist, impacting the feel, or tactile performance, of the paint.

Fig 15
Cross section 4, showing brown ground layers

In the *Crucifixion of Saint Andrew* Caravaggio applied two distinct brown-colored ground layers to the canvas as a preparatory base **FIG. 15.**[35] The cross section reveals that the lower ground (a) was applied in one thick layer, most likely to fill in the coarse, uneven raised warp-float texture of the canvas. Judging from the broad vertical and horizontal strokes seen in the X-ray composite, this layer was likely applied with a wide flat spatula similar to instructions described in Giorgio Vasari's *On Technique.*[36] Testing found that the lower ground was highly absorbent and reactive to moisture, immediately swelling and degrading upon direct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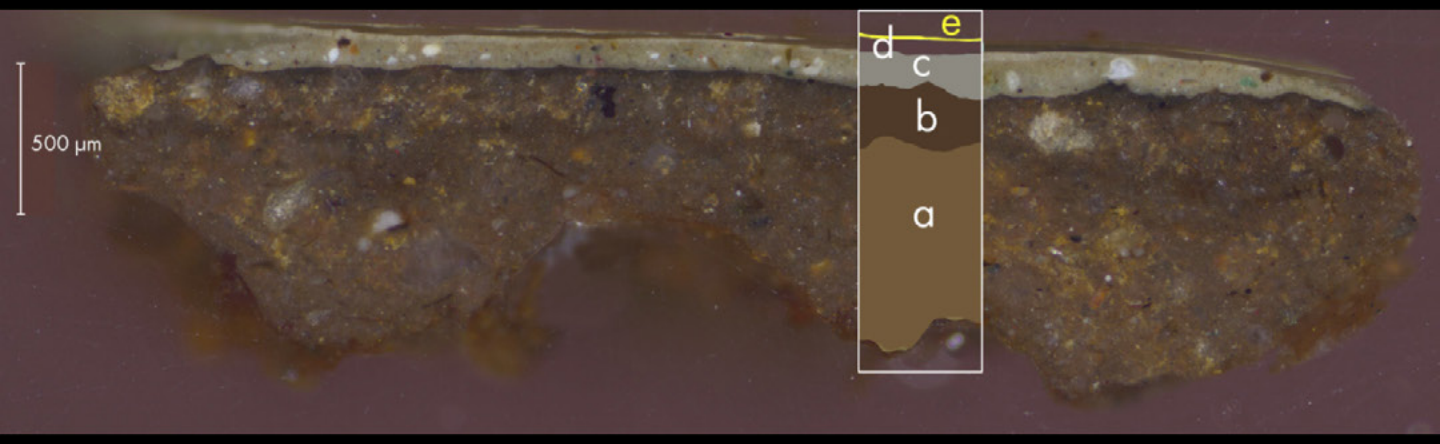
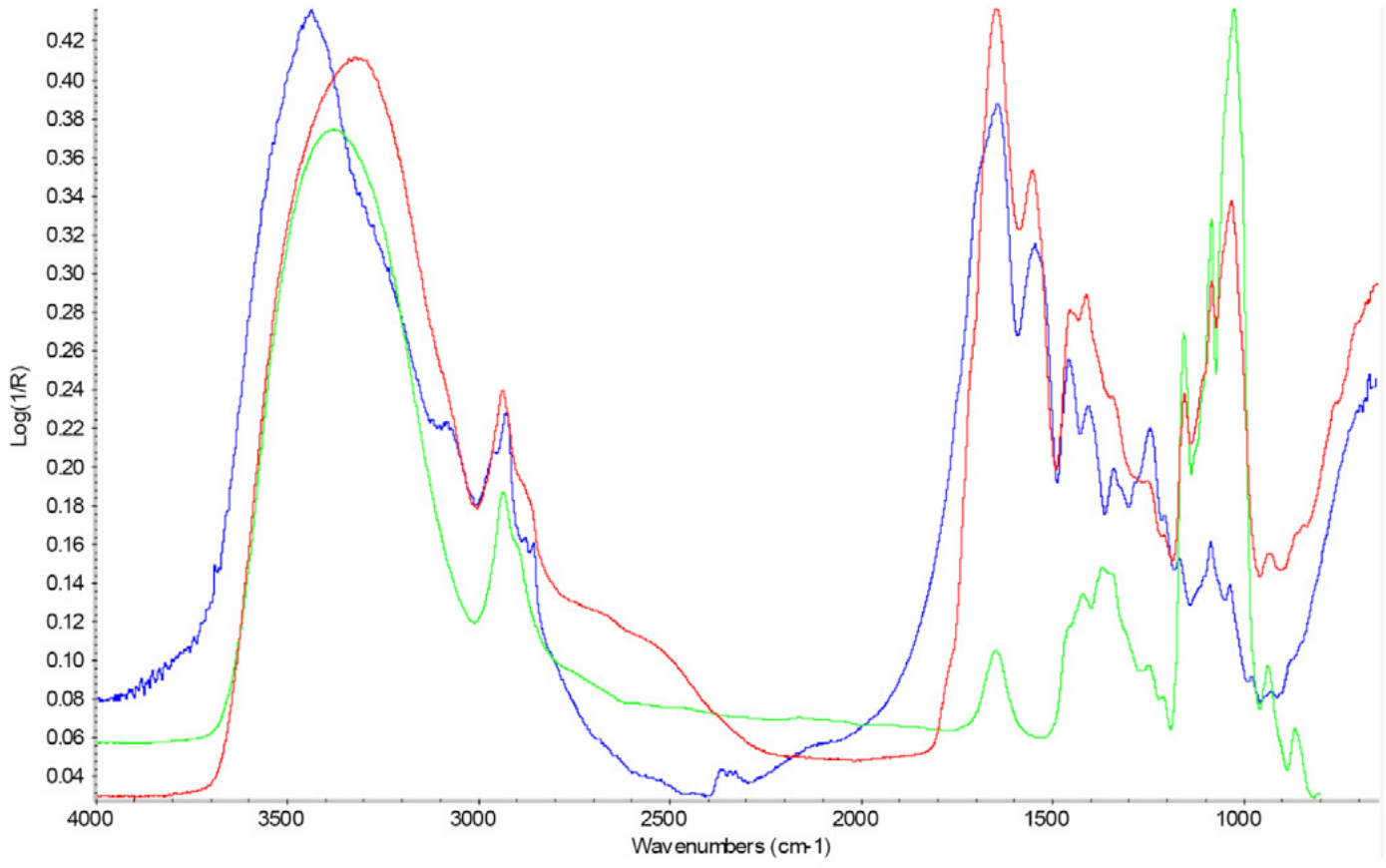

500 µm
e
d
c
b
a

contact with water. Curiously, an amber-colored substance was drawn out of the lower ground after the water had evaporated from the test areas. This indicated that the binder present in the lower ground was water soluble and could be quickly mobilized. Analysis with Fourier-transform infrared spectroscopy (FTIR) confirmed that the binder for the lower layer was composed of animal glue and possibly some starch **FIG. 16.**[37] However, the presence of starch in the lower ground could possibly be due to infiltration of the paste lining adhesive, which also contains a substantial amount of starch **FIG. 17.**

Fig 16
FTIR spectra of the lower ground layer compared to wheat starch and animal glue. Red: lower ground layer; green; wheat starch paste; blue: animal glue

In cross sections taken from various areas of the painting, the upper ground layer is more evenly applied and appears slightly darker under both normal incandescent light and long-wave ultraviolet (UV-A) irradiation **FIG 18.** The upper layer exhibited no observable swelling with water and was found to be bound in oil.[38]

Use of a scanning electron microscope equipped with energy-dispersive X-ray spectroscopy (SEM-EDS) established the elemental composition of the ground layers.[39] Elemental mapping with EDS found that both ground layers contained a similar distribution of coarsely to moderately ground pigments and bulking ingredients, largely composed of aluminosilicates or clay containing traces of titanium (possibly ilmenite), calcium carbonate, iron particles, pyrite, magnetite, bone or ivory black containing phosphorus, magnesium, trace amounts of azurite containing copper, and vermilion containing mercury. Lead white was mostly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Wavenumbers (cm-1)

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Fig 17
FTIR spectra comparing lower ground layer with lining adhesive. Red: lower ground; green: paste lining adhesive

In cross sections taken from various areas of the painting, the upper ground layer is more evenly applied and appears slightly darker under both normal incandescent light and long-wave ultraviolet (UV-A) irradiation **FIG 18.** The upper layer exhibited no observable swelling with water and was found to be bound in oil.[38]

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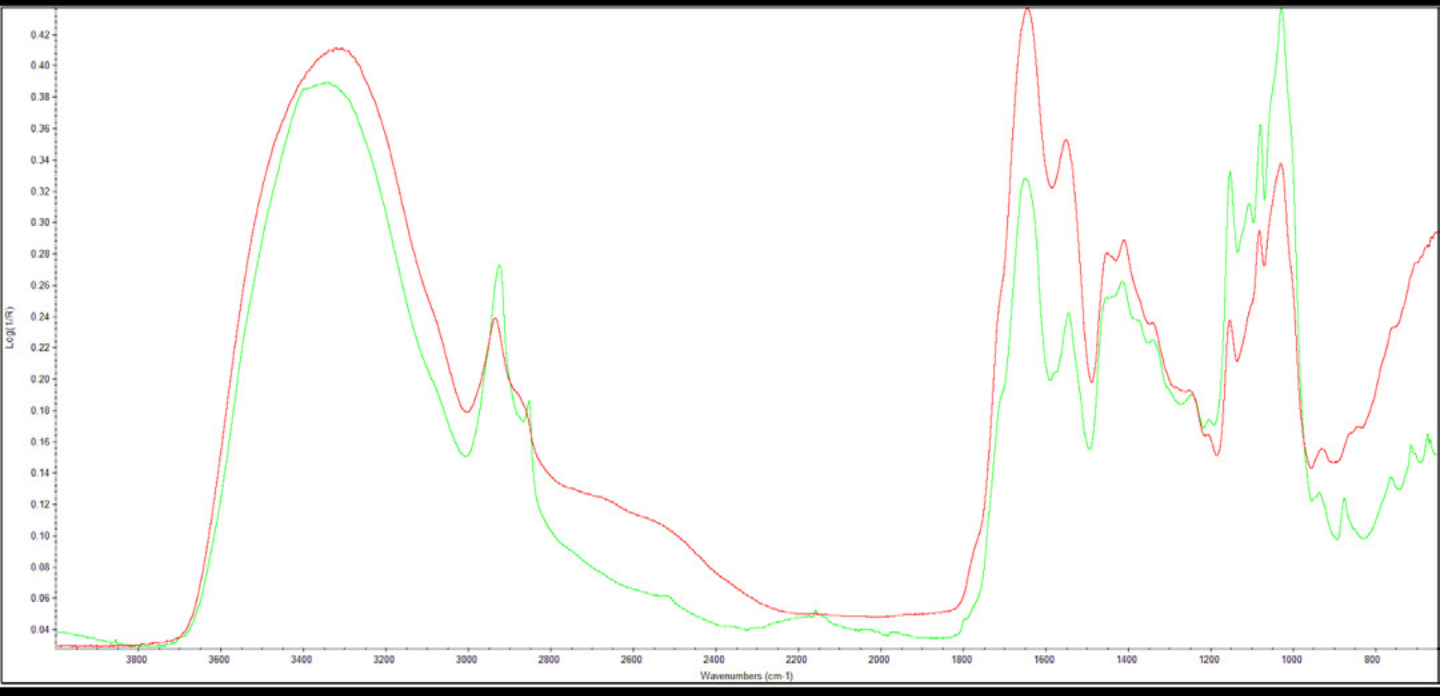
Log(1/R)
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1400
1200
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Wavenumbers (cm-1)

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Fig 18
Cross section 2, upper ground layer

In cross sections taken from various areas of the painting, the upper ground layer is more evenly applied and appears slightly darker under both normal incandescent light and long-wave ultraviolet (UV-A) irradiation **FIG 18.** The upper layer exhibited no observable swelling with water and was found to be bound in oil.[38]

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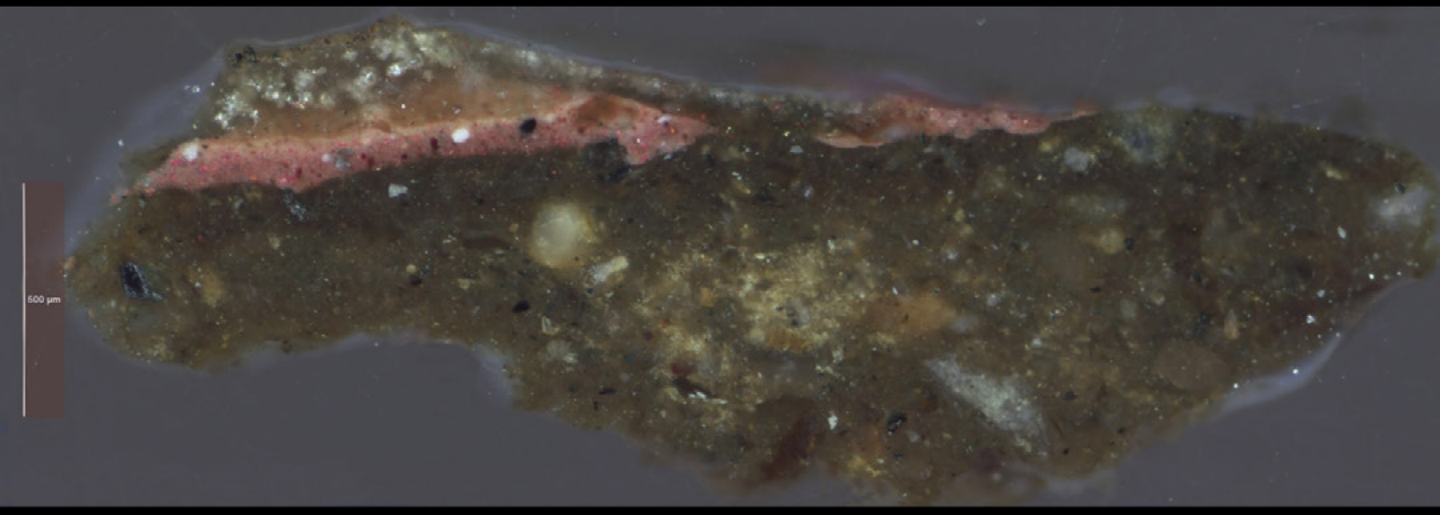
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absent, though a particle was detected in the upper ground layer in cross section 2. Raman spectroscopy (used in chemistry to identify characteristic structural fingerprints of molecules) verified individual pigment particles in cross section 2 **FIG. 19**. Another interesting discovery was the spherical aggregates of pyrite (iron sulfide) and pyrite framboids in the proximity of microfossils **FIG. 20**.[40] Similar pyrite spheroids in conjunction with microfossils were cited in the ground layer of *Saint Francis in Meditation* (Carpineto Romano), and pyrite particles were found in the ground layer of the *Madonna dei Palafrenieri* (Galleria Borghese).[41] However, until ground layers by other artists working in the same region and time period are analyzed with similar scrutiny, the significance of these microfossils and pyrite spheroids in Caravaggio's ground layers is unclear.

Fig 19
Cross section 2, pigment types

Ground Layer: Condition

Both ground layers are well adhered to each other and to the original canvas. However, extensive cracking in both ground layers is prevalent throughout the painting. Most noticeable are the more or less regularly spaced bands of straight horizontal cracks that span the painting's entire width. Horizontal cracks of this type are generally associated with paintings that have been rolled for transportation or storage. Located within these prominent horizontal cracks are networks of finer, more intricate cracking. These fine cracks often begin, terminate, or intersect the end points of the

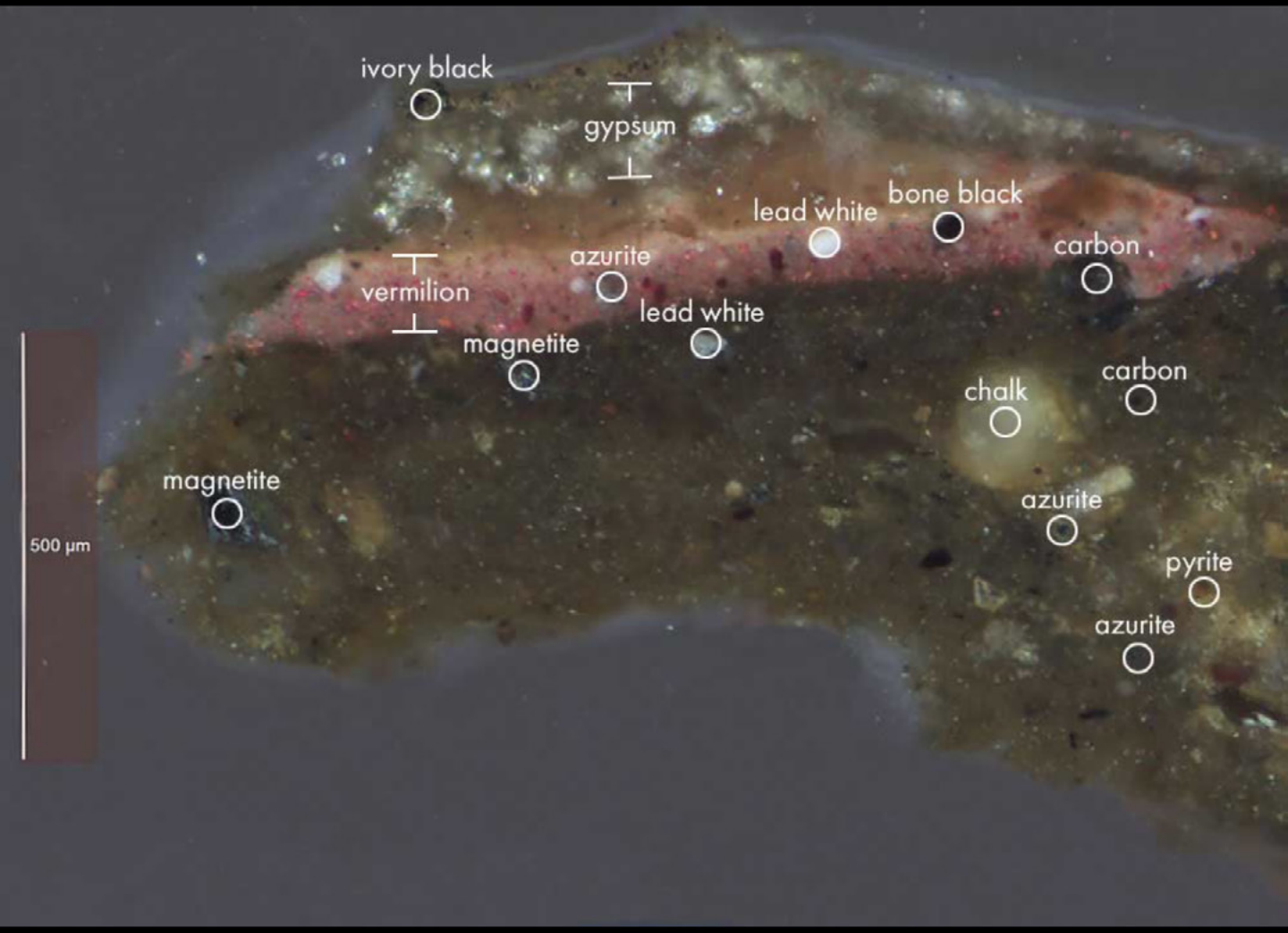
ivory black
gypsum
lead white
bone black
carbon
azurite
vermilion
lead white
magnetite
carbon
chalk
magnetite
azurite
pyrite
azurite
500 µm

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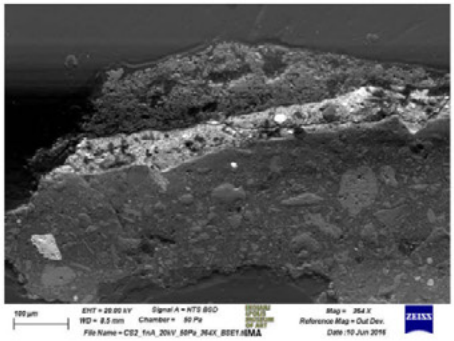
Fig 20
Cross section 2, pyrite framboids and microfossils. SEM photo: Greg Smith

Ground Layer: Condition

Both ground layers are well adhered to each other and to the original canvas. However, extensive cracking in both ground layers is prevalent throughout the painting. Most noticeable are the more or less regularly spaced bands of straight horizontal cracks that span the painting's entire width. Horizontal cracks of this type are generally associated with paintings that have been rolled for transportation or storage. Located within these prominent horizontal cracks are networks of finer, more intricate cracking. These fine cracks often begin, terminate, or intersect the end points of the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EHT = 20.00 kV
WD = 8.5 mm
Signal A = NTS BSD
Chamber = 50 Pa
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Reference Mag = Out Dev.
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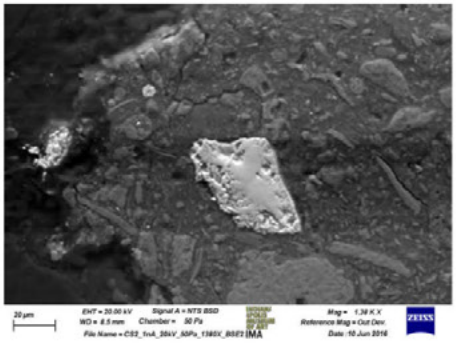
20 µm
EHT = 20.00 kV
WD = 8.5 mm
Signal A = NTS BSD
Chamber = 50 Pa
Mag = 1.39 K X
Reference Mag = Out Dev.
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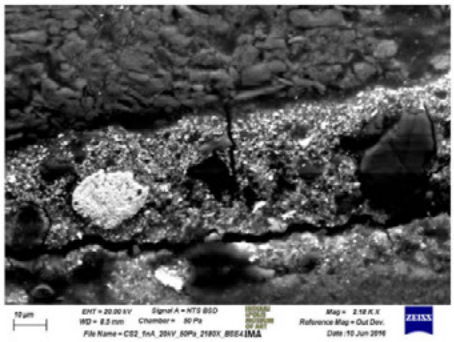
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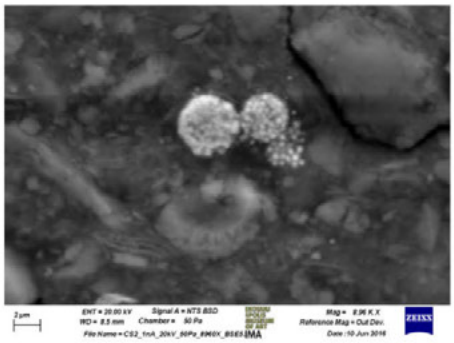
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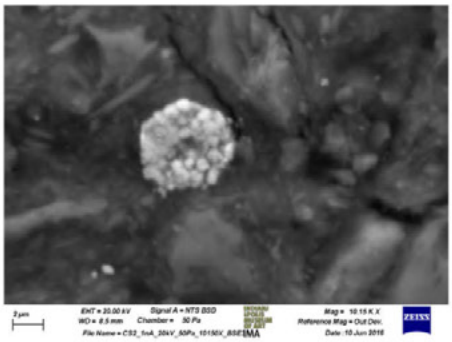
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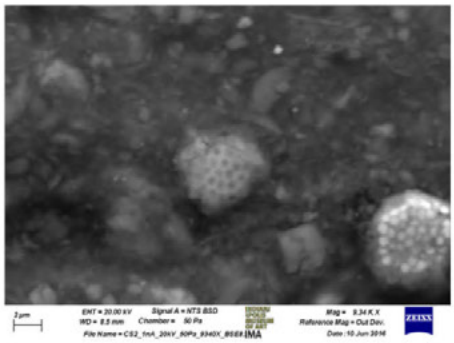
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floating warp threads, and likely indicate dimensional stress and strain points within the weave structure (see fig. 9).

While the ground layer remains well adhered to the canvas, its hygroscopic composition would suggest that it is quite reactive to changes in humidity and temperature. The humectant nature of the ground was confirmed anecdotally when samples of the ground were shipped to Indianapolis for analysis. Upon their arrival, Smith reported that the ground samples had apparently liquefied in the humidity within the loosely sealed vial chambers, extracting and depositing the aqueous binder underneath the samples. If the lower ground can readily liquefy in humidity, it can potentially solubilize and mobilize the binder on a microscopic level.

Technical Imaging: Infrared Radiation

A set of seventy digital infrared images were assembled in Photoshop to produce a full-scale IR capture of the entire painting.[42] On close inspection, previously observed incisions made into the ground layer could, for the first time, be seen with greater clarity. These high-resolution IR images also revealed additional incisions not previously known or recorded in the area of the drapery of the figure standing on the ladder.

Until recently, evidence of graphic underdrawings in Caravaggio paintings has been elusive or nonexistent.[43] In 2010, a paper presented at the CHARISMA workshop in Florence identified underdrawing in carbon black in IR with

a detector and filter optimized to wavelengths in the 2,265 nanometer range.[44]

Primary Incisions and Markings in the Ground Layer

After the upper oil-containing ground layer had sufficiently dried, Caravaggio's first marks often involved the use of incisions. There is consensus among scholars that these incisions designated positions or contours of figures and compositional elements. Incisions in this painting have several different characteristics that seem related to their function. The most concentrated grouping of incisions is underneath the drapery in the upper torso of the executioner on the ladder, delineating contours of his raised arm, torso, and the centerline of his spine. These incisions have a freely drawn, curvilinear quality that refer only to the underlying anatomy of the figure, and not the drapery **FIG. 21**. Ross Merrill, and then later, Keith Christiansen, Caravaggio expert and curator at the Metropolitan Museum of Art, had noted a number of incisions in the area of the drapery; however, recent higher resolution infrared captures obtained with the Osiris IR camera reveal greatly expanded numbers and range.[45]

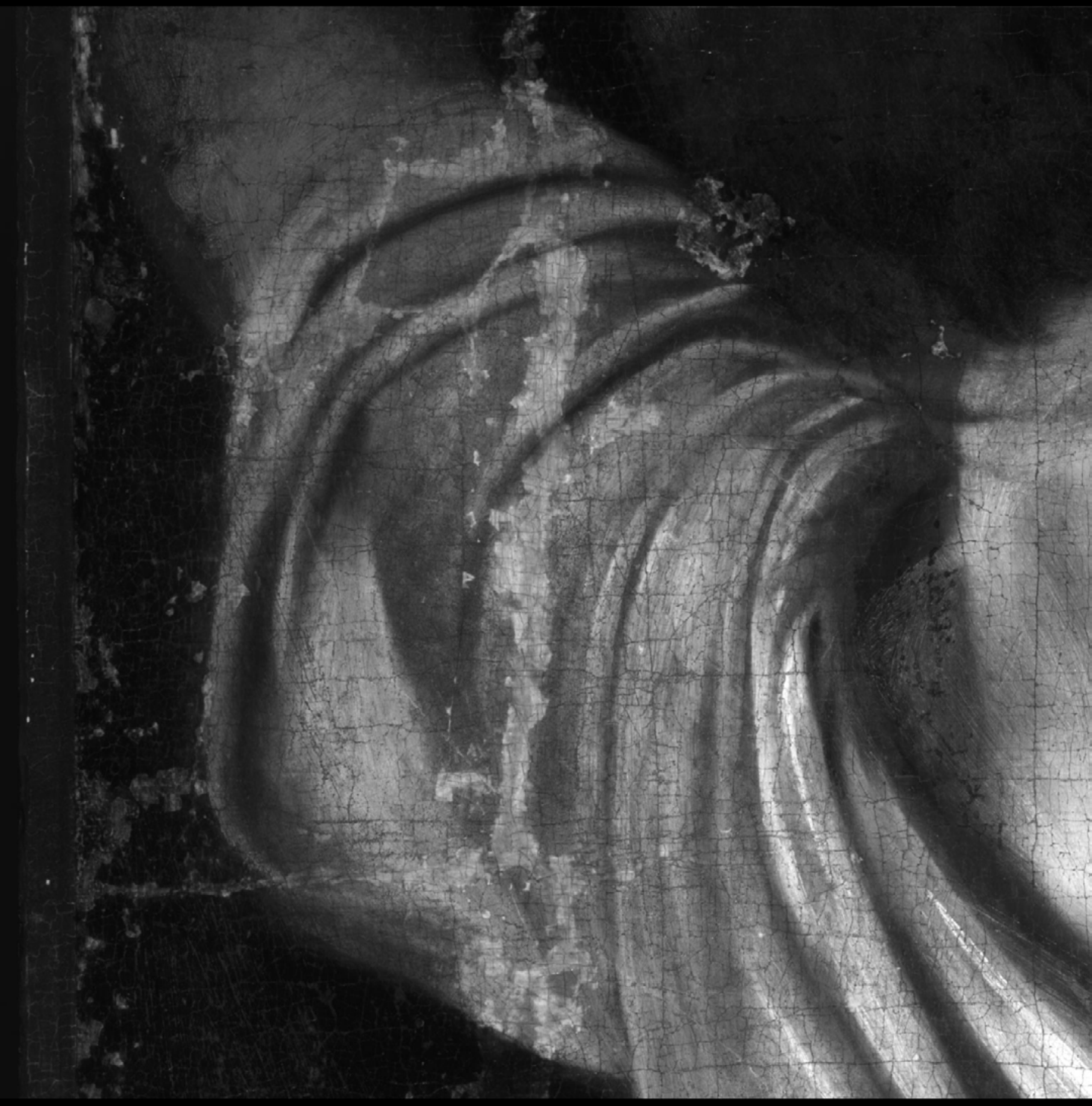
Fig 21
IR image of the upper left quadrant with incisions mapped in yellow

Furthermore, the recent removal of the heavy varnish layer and previous retouching has improved the textural reading of the paint surface, facilitating the discovery of an extraordinary number of previously hidden incisions throughout the painting. These are discussed in greater detail in the Conservation section.

Nearly all the incisions underneath the drapery of the figure on the ladder are also seen in the X-rays and infrared reflectographs. This is because the early applications of lead white paint, or *abbozzo*, [46] have filled in the shallow grooves created by the sharp tool used to scratch the incisions into the ground layer. Incisions in this area are visible in the X-ray only because of the increased radio-density due to their thickness. Likewise, the increased reflectance of the incisions filled with lead white enables their detection in the infrared spectrum **FIG. 22.**[47] It is also common to see cracks running through the center of the incisions in the X-ray images, as the scoring has weakened the structural integrity of the ground layers.

Fig 22
IR image of the shoulder of the executioner on the ladder revealing the fine white lines cut into the upper ground layer that were filled with lead white abbozzo

The deep and prolific cracking in the ground and paint layers is another major factor complicating the detection of incisions. Quite often an incised line will merge with a crack, or a series of cracks, and will correspond to a contour of a figure or article of clothing. In the cases where incised lines merge with or seem to continue as cracks, only the incised lines themselves were diagrammed and not the assumed continuations. Of all the cracks likely caused by an incision, the one located inside the contour of the saint's left leg is particularly intriguing. Beginning above the ankle and running the length of the foot, this crack closely mirrors the lower leg's contour **FIG. 23.**[48] Near this crack, a curvilinear marking drawn into nearly black wet paint defining the outer contour of the saint's ankle was likely created with a bluntly pointed tool, possibility a brush handle. This line,



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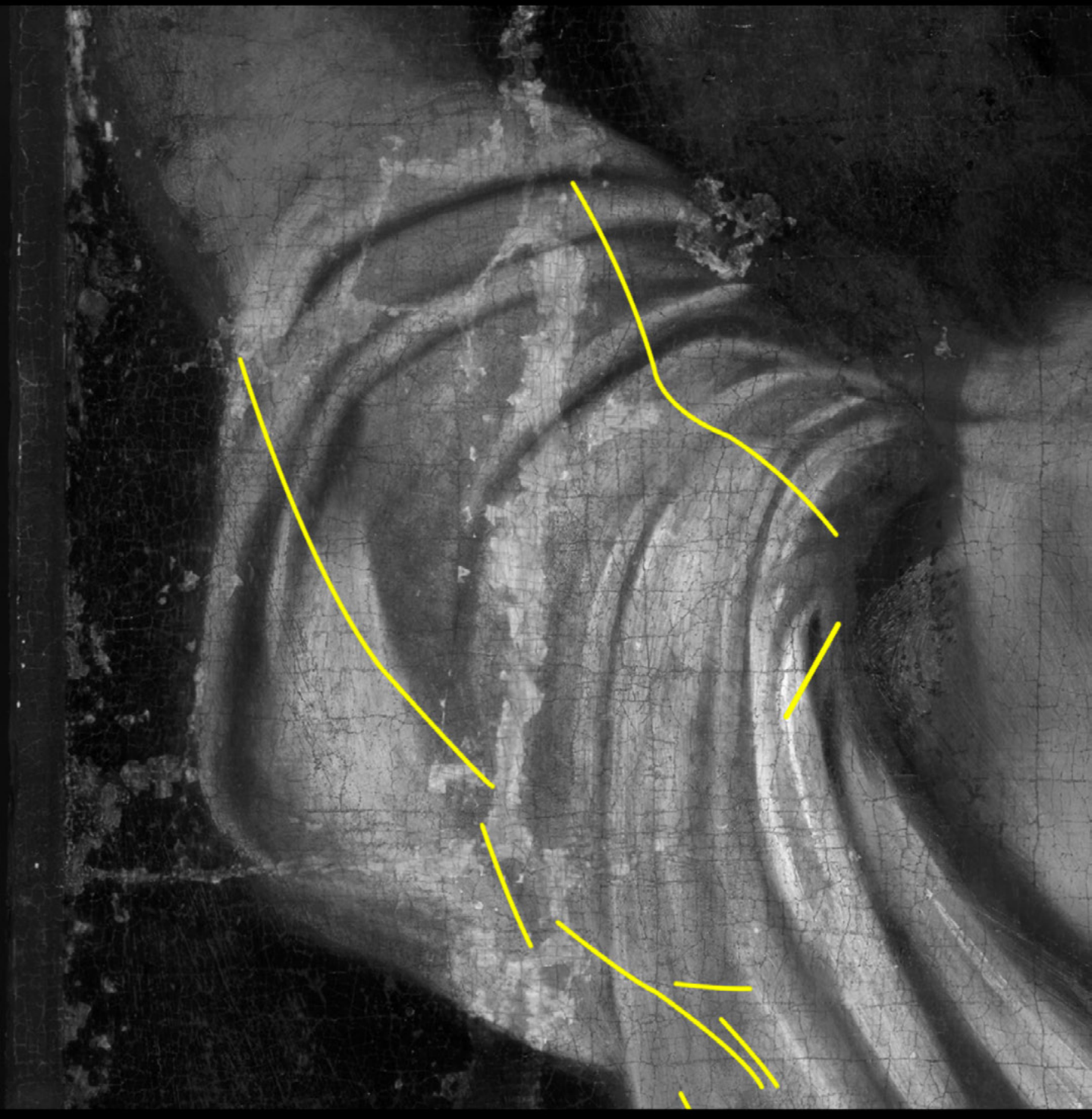

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Fig 23
Normal light overlaid with X-ray to emphasize how underlying abbozzo corresponds to final layers

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which reveals the lighter underlying layer, appears to be intentional, separating the edge of the ankle bone from the darker shadow that is cast over the figure in the background. Another short mark where a top layer of wet paint has been pushed aside, revealing a darker underlayer, appears above the saint's eyebrow. This horizontal Y-shaped mark has an ambiguous quality; it appears to have occurred before the uppermost paint had dried. However, it is also crude and out of character with the more finished surrounding paint, raising the question of whether the artist intentionally applied it.

End Notes

35. The first, lower, water-soluble ground layer varies in thickness between 200 and 700 micrometers (µm); the second, upper ground layer consistently varies between 100 and 200 µm.
36. Giorgio Vasari, *Vasari on Technique* (New York: Dover, 1960; first published 1550), 88. In the chapter "Of Painting in Oil on Canvas," 236–37, Vasari describes a mixture made from "flour and walnut oil with two or three measures of white lead put into it, and after the canvas has been covered from one side to the other with three coats of smooth size, this paste is spread on by the means of a knife, and all the holes come to be filled up by means of the artist."
37. The FTIR analysis, performed in collaboration with Gregory D. Smith of the Indianapolis Museum of Art's conservation science department, used the Thermo Nicolet 6700 spectrometer (transflection mode). A fragment from the lower ground was placed on a MirrIR low-e microscope slide; deionized water dripped on the fragment leached out the water-soluble components.
38. Pyrolysis–gas chromatography–mass spectrometry (Py-GC-MS) analysis was positive for oil; however, the exact type has not been established at this time.
39. Equipment used: Zeiss Evo MA15 SEM under variable pressure conditions using a five-segment back-scattered electron detector or a Bruker Quantax 200 EDS detector. See individual cross sections for more information.

40. Pyrite framboids averaging 2 µm in diameter were discovered with SEM-EDX at 9,340x.
41. Matteo Positano, Irene Aliatis, and Claudia Conti, "Micro-Destructive Investigations," in Vodret, *Caravaggio: Works in Rome*, 1:313, fig. 3; 1:314, fig. 5.
42. Equipment used: Cleveland Museum of Art's Osiris infrared reflectography camera, indium gallium arsenide (InGaAs) detector array sensitive to 900–1,700 nanometers (nm).
43. Roberto Bellucci and Cecilia Frosinini, "New Evaluations on Caravaggio's Methods of Underdrawing: Art Historical and Scientific Challenges," in Ciatti and Brunetti, *Caravaggio's Painting Technique*, 51.
44. Ibid., 56.
45. Keith Christiansen, "Caravaggio and 'L'esempio davanti del naturale,'" *Art Bulletin* 68, no. 3 (1986): 421–45. Christiansen mentions "two incisions on the back of the man on the ladder, at left, just inside the contour of the white shirt," 436. In the 1976 conservation report, Merrill noted incisions corresponding to the shoulder and outer contour of the standing figure's torso.
46. *Abbozzo* is an Italian word for "sketch" now commonly used by Caravaggio scholars when referring to the underlying brushstrokes of lead white paint visible in X-rays and often through the finished paint layers.
47. Equipment used: Cleveland Museum of Art's Osiris infrared reflectography camera, indium gallium arsenide (InGaAs) detector array sensitive to 900–1,700 nm.
48. In "Caravaggio and 'L'esempio davanti del naturale,'" 436, Christiansen mentions that this cracking "may be the result of an underlying incision."

Paint Construction and Painting Technique

In normal daylight, the thick reflective varnish layers, opaque retouching, and previous abrasions all combined to obscure the reading of the paint layer's nuanced manipulation. Nevertheless, many of Caravaggio's earliest applications of paint can be studied with both X-ray and infrared reflectography. X-rays are particularly valuable in understanding the artist's application of the abbozzo, the paint containing lead white used to sketch in areas predetermined to be lighter in value **FIG. 24**. This is because the absence of radio-opaque materials in the ground layer provides a perfect backdrop for viewing the X-ray–blocking properties of the lead-based abbozzo. There is a free, yet decisive quality to the abbozzo's brushwork. Good examples are the fluid and rapid brushstrokes used to define the muscles and first placements of highlights in the shoulders and back of the figure on the ladder. This same approach was used to rough in the saint's torso, where the abbozzo defines his pronounced rib cage and the elongated muscles of his shoulders and arms. Only the stark highlights are articulated at this stage, leaving the passages of shadow and middle values for later.

A few passages of the abbozzo can also be seen in normal daylight emerging through later applications of paint that have grown transparent with age, or on occasion, revealed

Fig 24
Normal light overlaid with X-ray to emphasize how the underlying abbozzo corresponds to final paint layers

by abrasions caused by overcleaning. A good example of this is a light, briskly applied abbozzo stroke just above the trousers of the figure on the ladder, which can be seen peeking through later applications of paint **FIG. 25**.

At or near the time he applied the abbozzo, it appears that Caravaggio used a black, carbon-rich paint to begin delineating the contours that mostly reside in areas of shadow. These fairly wide strokes, faintly visible in normal daylight, are best seen in the recent infrared reflectograms.[49] They are most evident around the arms, torso, and legs of both Saint Andrew and the figure standing on the ladder, often delineating or redefining edges or contours. They also typically exhibit a fluid quality similar to the freely applied nature of the abbozzo. Similar wide underlying strokes of black, carbon-rich paint used to define or possibly emphasize contours in the early stages of painting can be seen in the infrared images of many other Caravaggio paintings.[50] An excellent example of the fluid carbon-containing black outline can be seen around the neck and shoulders of Christ in the infrared image of *Crowning with Thorns* (Kunsthistorisches Museum) **FIG. 26**.

Fig 25
Initial abbozzo stroke of the executioner on the ladder

In the Cleveland painting, it appears that after laying in the abbozzo and preliminary contours, Caravaggio began creating the effects of volume, light, and shadow in his figures with relatively few pigments. For example, the musculature and skeletal structures of the saint's torso are simultaneously created through the relative thickness of the flesh tones, which are laid over the abbozzo and the darker

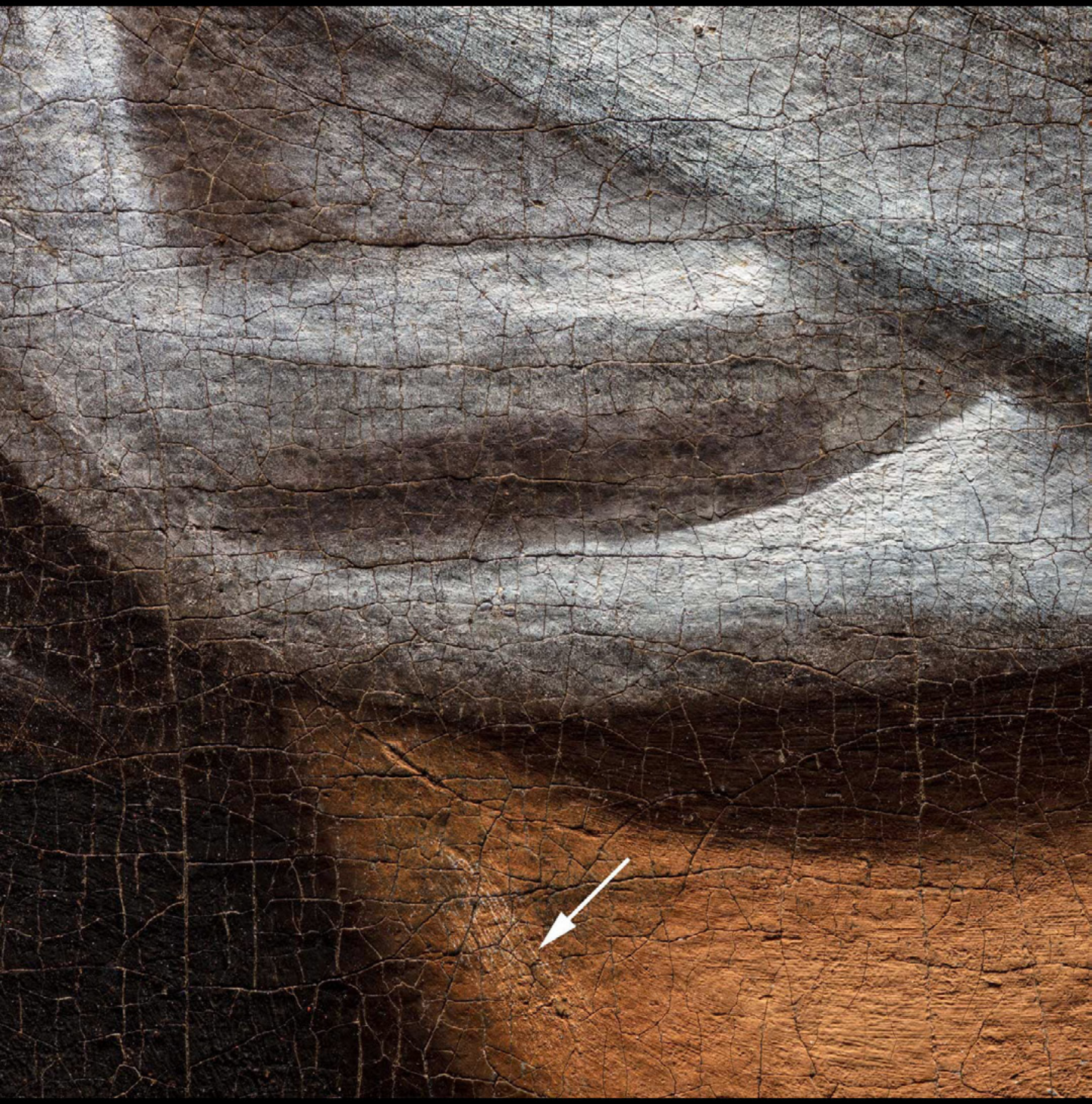

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Fig 26
IR image of *Crowning with Thorns*

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oil ground color. Caravaggio exploits the optical effects of placing lighter tonality over the darker ground layer; rather than adding a darker pigment to the flesh tones in order to create the faintly shadowed recesses between the ribs, Caravaggio simply applied less paint, allowing more of the dark underlying ground to emerge. Possibly the best example of this technique is illustrated in the saint's rib cage and torso, where much of the initial anatomical form was first laid out in the abbozzo, then modified by scumbling in lighter flesh tones to create volume. The artist essentially bridged and softened the forceful strokes of the abbozzo with darker brown tones of the upper oil ground layer. As these lightly scumbled flesh tones become thinner along the shadow's edge in the ribs and torso, cooler half tones are created in the recesses of the rib cage. Caravaggio's careful control of opacity and transparency by altering the paint thickness is one of the more astounding features of his technique.

The *Crucifixion of Saint Andrew* bears many other similarities to the *Crowning with Thorns* in terms of paint handling. Even though the ground in the *Crowning* appears lighter and warmer overall, a similar strategy in utilizing these underlying tones is readily apparent, especially in the soldier's armor, which is in remarkable condition. Caravaggio intentionally allowed the warm tonalities of the underlying layer to emerge in areas adjacent to bright lead white highlights. These warmer tones appear as reflections emerging from the black metallic armor. While the paint

layers in the *Crowning* show some abrasions and increased transparency, the handling of the flesh tones is also remarkably similar to the *Saint Andrew*. The underlying warmth of the ground provides the perfect half tone in nearly all areas of exposed flesh. For example, mid-range highlights, composed of ochre tones mixed with white, are lightly scumbled to define the pectoral muscles in Christ's chest. Thinly applied, transparent darker tones that define the deepest shadows use the underlying warmer reddish tones to softly bridge the highlights. A similar approach was used in the rendering of the saint's rib cage, except the underlying tonality supplied by the ground is much darker, imposing a slight greenish hue.

One of the most extraordinary aspects of Caravaggio's technique is his superb handling of the contour lines that surround his figures. Remarkably nuanced, these contours describe the muscularity with subtle angular facets. Sharp black lines often reinforce changes in the direction of the line. At times, these refined sharp lines enhance the dramatic chiaroscuro effects, as in the saint's neck and shoulder where the light is most concentrated. Equally masterful is Caravaggio's use of softly blended contours that smoothly retreat into darkness.

A good example of both sharp and soft contours is in the saint's right armpit, where a sharpened contour line defining the trapezius muscle meets the wider soft contour of the lower rib cage. Another example, difficult to see because of the cracking, is in his crossed legs. Here, the contour lines

sharpen as the front quadriceps muscles reach the knee. The contour along his thigh, which falls over the ladder, quietly recedes into shadow.

Pigments

Caravaggio used relatively few pigments in the *Crucifixion of Saint Andrew*. According to handheld X-ray fluorescence (XRF) analysis,[51] the darker colors in the background are composed mainly of iron-rich earth pigments containing variable amounts of manganese, indicative of ochre and umber pigments. The flesh tones are generally composed of lead white and earth pigments. The warm tones seen in the saint's neck and the executioner on the left contain only lead white and iron-rich earth pigments. Only trace amounts of vermilion or cinnabar, indicated by the presence of mercury, were detected with XRF in the reddish tone around Saint Andrew's neck; otherwise, mercury was completely absent from the flesh tones. Taken from a highlight of the saint's pectoral muscle, the sample in cross section 7 revealed a double layer of lead white with a prominent particle of green earth (celadonite), fine transparent yellow particles composed of iron, confirmed as yellow ochre, and a small red particle confirmed as hematite. The green earth may have been used to cool down the effects of the warmer tones of red and yellow ochre.

The thickly applied green pigment used in the soldier's green waistcoat was identified as malachite.[52] After cleaning, it appeared that a thin, semitranslucent, dark brown layer

may have originally been applied over the top of the light green malachite pigment to tone back its intensity. Further examination of this possible toning layer under UV radiation with the stereomicroscope does reveal a random distribution of an extremely thin, finely cracked coating with a faint greenish autofluorescence, typical of a natural resin. When examined under visible light, both cross sections 9 and 10 from the green waistcoat indicate a medium-rich, brownish-green crust over the lighter green malachite pigment, which is quite possibly what appears as a translucent brown tone seen over the malachite pigment. However, the darkened crust visible in both cross sections does not emit this faint greenish autofluorescence seen over the paint surface. Instead, the crust displays the same dark UV absorption of the surrounding malachite particles, indicating that the brownish crust is likely part of the paint layer. Therefore, what might appear as an intentional tone may actually be a natural discoloration occurring within the paint layer, or possibly a darker copper resinate paint applied over the still wet malachite layer, which subsequently turned brown.[53] In either case, the faint fluorescence randomly scattered over the green waistcoat seems not to be directly tied to the brownish crust seen in the cross sections.

Vermilion was detected in only two passages of the painting: the saint's intense red drapery and the soldier's salmon-colored pants. According to XRF readings, vermilion was completely absent in red paint used in the garment of the figure on the far right. A thin, fairly intense

transparent red can be seen in daylight in the interstices of the highlights on the saint's drapery; past cleanings are likely responsible for removing some of these transparent red tones. The presence of an organic red lake colorant glaze in the highlights of Saint Andrew's drapery could not be confirmed. However, the presence of a red lake pigment in the darker folds of the figure in the red garment seems likely according to the particle morphology and the EDS spectra.[54]

Cross section 2 from the salmon-colored paint layer of the soldier's pants reveals a complex mixture of vermilion, lead white, iron-containing earth pigments, and particles of malachite that were likely used to reduce the intensity of the vermilion. Darker red transparent particles dispersed in the lower portion of this layer exhibit an intense fluorescence under UV irradiation, characteristic of an organic red lake pigment.[55] This same salmon-colored paint layer has a thin yellow-white band, or crust, with fine lighter red particles, while the darker, more transparent particles are located below the light band. This feature could indicate surface fading of the salmon-colored paint layer and loss of the organic lake colorant due to exposure to light.

The top layer of paint used in the highlight of the yellow pants of the executioner on the ladder is composed of lead-tin yellow type II, yellow ochre, and lead white. XRF spectra of the trousers detected the presence of tin in the yellow paint.[56] In cross section 1 from this area, Raman spectroscopy confirmed that the large, crystalline, light yellow particles are lead-tin yellow type II, and the presence

of lead white, and the darker, smaller, semitransparent yellow particles are yellow ochre.[57]

The elderly woman's dark blue-green blouse is largely composed of azurite, darkened with carbon black. A thin yellow-red layer underneath, matching the flesh tones found in her neck, adds the slight greenish tone to the blouse. XRF spectra gathered from the area of her shoulder strap indicates the presence of a copper-containing pigment, and also lead, undoubtedly linked to the strokes of lead white of underlying abbozzo. The presence of azurite and carbon black in cross section 1 was confirmed with Raman spectroscopy. The elderly woman's sleeve, which appears much grayer than her blouse, contains only trace amounts of a copper-based pigment, earth pigments, and lead white.

The red garment of the figure on the far right is composed of a dense layer of finely ground hematite (red ochre) applied atop a thick layer of carbon black as seen in cross section 3. This pigment's identity was confirmed with Raman analysis. XRF spectra of the highlights in the garment's folds indicate the presence of lead white.

Dark brown paint in the background is composed mostly of iron-rich earth pigments, including umber. Cross sections of the background areas in 13 and 14 reveal that the paint layer was applied in an extremely thin layer compared to the thickness of the ground. XRF spectra of these areas indicated a major intensity of iron and a minor intensity of manganese, indicative of umber pigments. EDS maps of cross section 14 indicated overlapping signals of both iron

and manganese in the top layer, providing additional evidence for the presence of umber.

Pentimenti and Artist Changes

One of the most intriguing passages of the painting is the pentimento of the initial placement of the elderly woman's hands clasped in prayer near her throat, which has emerged through the lower portion of her prominently painted goiter. Here, Caravaggio opted to paint over her raised hands, moving them to the bottom corner of the painting below the executioner's feet. Both X-ray and infrared images reveal the pentimento in dramatic fashion. A short, fine incised line cut into the ground that marks the outside edge of the overpainted forearm, discovered in an infrared image, further confirms Caravaggio's initial intent in positioning her uplifted hands even before applying the abbozzo. Further examination of both X-ray and infrared images indicated that the upper portion of the goiter and the surrounding distortions of the sternocleidomastoid muscles of her neck were present from the beginning. This suggests that at one point her clasped hands were only partially blocking the goiter, before they were moved to the bottom edge and the goiter was fully painted and visible. It is possible that tight placement of her raised hands against the legs of the executioner would have created a spatial discrepancy within the painting. It is easy to see how the lack of space between the elderly woman and the ladder forced Caravaggio to find an elegant solution. By positioning her

arms along the bottom, her right elbow echoes the shape of the corner and allows the ladder to fall in front of her left hand and elbow, creating depth and opening up the space in this densely packed area. Caravaggio painted out her raised hands by completing the lower section of the goiter and neck muscles. The initial placement of her raised hands has become more visible over time with the increased transparency of the paint layers.

Another subtle, yet significant area of change occurs with the initial placement of the soldier's profile, painted with a lead white paint. Here, probably to adjust the direction of the gaze, Caravaggio moves the contour of the soldier's profile down and to the right by about two centimeters. This change, visible only in the X-ray image and photographs taken during cleaning, reveals the positions of both contours. In this case, however, Caravaggio completely painted out the first placement of the profile with a heavy black paint to redefine the present contour. This change was starkly revealed in the images from the 1974 restoration where the cleaning revealed an early aggressive overcleaning that stripped away the more vulnerable black paint. The X-ray also reveals lead white–containing flesh tones underneath the soldier's beard, indicating that Caravaggio first worked out the position of the jaw well before painting the beard **FIG. 27**.

Fig 27
X-ray of the abbozzo underneath the soldier's beard

Paint Layer: Condition

Most seventeenth-century paintings have undergone many treatments with little or no documentation, and this painting is no exception. Even the most recent cleaning from 1974 was documented only with a questionnaire and a limited number of photographs. Therefore, conclusions about the previous treatment can be drawn solely from visual examination and chemical analysis. The paint is in much better condition in the thickly applied passages of the lighter flesh tones and draperies, which contain robust lead white paints that are inherently more resistant to cleaning solvents. It is clear that an aggressive cleaning occurred well before the 1974 treatment and after most of the cracks had formed, as solvents and friction from rubbing have caused significant abrasions to the top ridges of the cracked and cupped paint. The paint layers are better preserved within the lower concave depressions of the cupped paint. Abrasions to the top ridges of the cupped paint have exposed more of the dark underlying preparatory layers, accentuating the visual effect of the cracks.

Several types of cracks permeate the paint layers. The most noticeable are the pronounced horizontal cracks that occur at regular intervals over the entire painting, characteristic of paintings that were rolled for transportation or storage. Within the horizontal crack structure are secondary networks of cracking that run vertically and diagonally. These secondary cracks are nearly as deep and wide as the horizontal cracks, but exhibit slightly less cupping.

A series of finer, more delicate cracks lie within this secondary crack network. These cracks are thinner and shallower, revealing the edges of the dark underlying ground layer and correspond to cracking (seen in the X-ray positive) that intersects with the previously mentioned floating, open-weave structure in the original canvas. Extremely delicate networks of craquelure or microfissures are present on the surface of the paint within this secondary network. These cracks, visible at higher magnifications (25–50x), are present in areas where the paint layer is extremely thin or abraded, often revealing the ground layer. Finally, one can actually see even finer microscopic cracking around exposed particles protruding from the ground layer. These translucent white particles are likely chunks of calcium carbonate that also appear in the cross sections.

End Notes

49. Equipment used: Cleveland Museum of Art's Osiris infrared reflectography camera, indium gallium arsenide (InGaAs) detector array sensitive to 900–1,700 nm.
50. Maria Beatrice De Ruggieri, "Caravaggio's Painting Technique: Compositional Processes and Material Structures," in Vodret, *Caravaggio: Works in Rome*, 117: "Far more evident in the two Cerasi canvases are the numerous dark brushstrokes outlining the figures, again clearly revealed by reflectography and present in other paintings very close to these, such as the *Madonna of the Rosary*."
51. Equipment used: Bruker Tracer III-SD handheld XRF spectrometer.
52. The green pigment in this area produced a strong copper peak using the handheld XRF spectrometer and the SEM-EDS. Malachite was confirmed by Raman spectroscopy. See cross section 9.
53. For more on the brown discoloration of copper resinate green, see Hermann Kühn, "Copper Resinate (Transparent Copper Green)," in *Artists' Pigments: A Handbook of Their History and Characteristics*, ed. Ashok Roy (Washington: National Gallery of Art, 1993), 2:150.
54. See the SEM image and spectrum for particle (2) for cross section 15.
55. See layer (c) and elemental maps in cross section 2.
56. See XRF spectra for locations 9 and 10.
57. See the Raman spectrum for lead-tin yellow type II particles in cross section 11.

Analysis of Surface Coatings Prior to Treatment

The lack of a formal treatment report prompted conservator Ross Merrill to submit a questionnaire to the restorer, Jan Dik, who last treated the painting in 1974. The questionnaire allows us to confirm the type and stratigraphic arrangement of materials used in his restoration. Dik writes: "Very thin Griffin varnish applied over whole picture before retouching. An extra varnish with 95% alcohol and 5% of a natural resin was applied on top of the retouches, to protect them before the final surface of Griffin varnish was sprayed on.[58]

To determine the stratigraphy and type of varnish used, four tiny samples, two along the bottom and two along the right edge, were taken and prepared into cross sections for analysis under normal light and UV irradiation **FIG. 28**. Two of the four cross sections, number 2 from the bottom and number 4 from the right edge, were the most successful in preserving all of the layers of the ground, paint, and surface coatings. Additional scrapings of only the surface coatings were taken to identify and verify the materials used in the last conservation treatment. A sample of the upper varnish analyzed with FTIR was found to contain large amounts of lac.[59] Lac or shellac (*gomma lacca* in Italian) is technically a natural resin varnish, but is rarely used as a picture varnish in the United States; its use as a coating or

Fig 28
Locations of cross sections 2 and 4

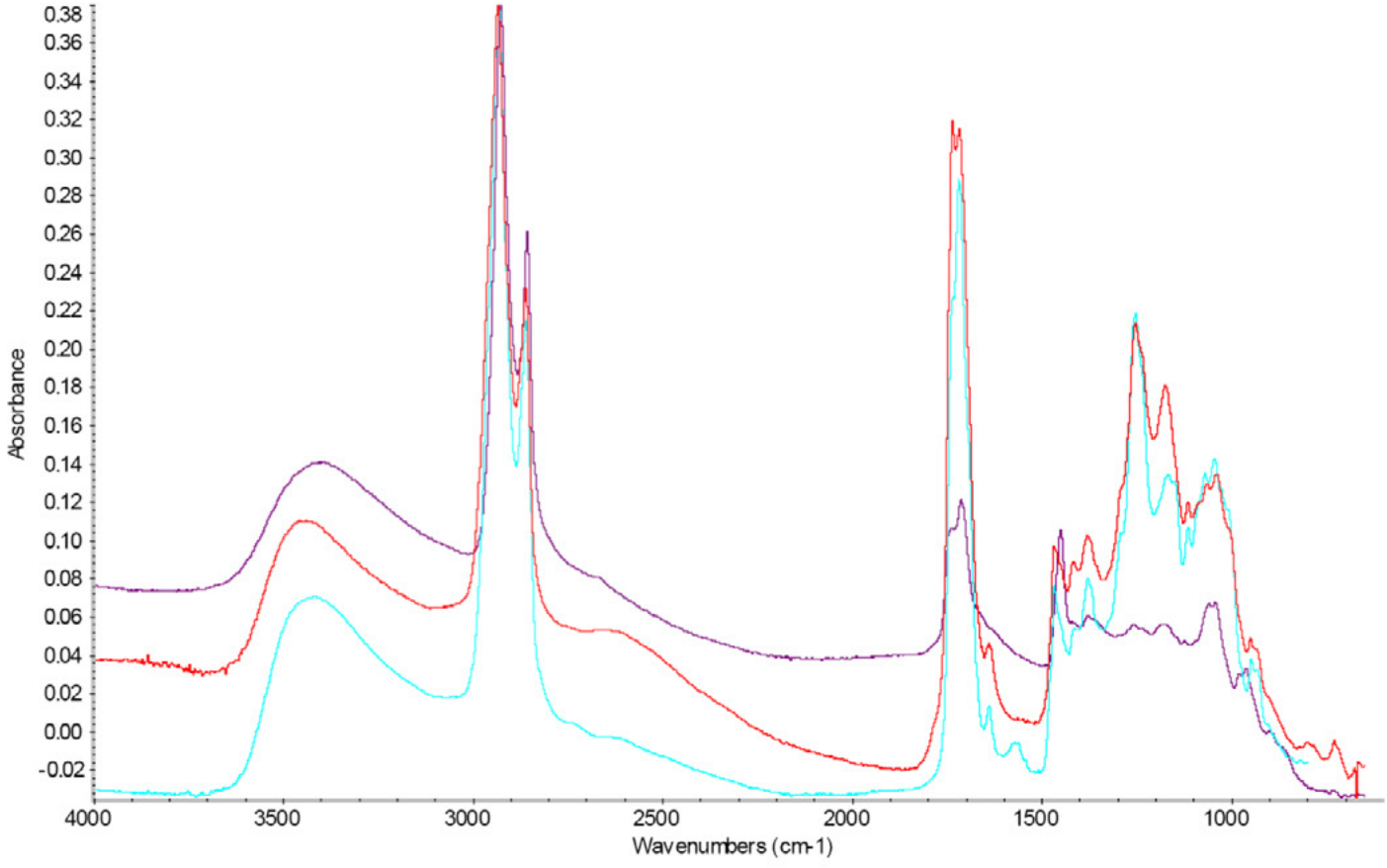
CS04
CS02

sealing layer between varnishes may be more common among European restorers.

The shellac layer was brittle, insoluble in xylene, but instantly soluble in alcohols: isopropanol and ethanol. But the coating below the shellac layer and directly over the paint was found to be softer and readily soluble in aromatic hydrocarbons, for example, xylene. Curiously, the FTIR spectrum of the lower varnish layer exhibited some peaks consistent with a ketone resin (Griffin), but also contained a considerable amount of shellac **FIG. 29**. A rare aged sample of Griffin varnish was obtained from the conservation department of the Detroit Institute of Arts. This sample, later analyzed with pyrolysis–gas chromatography–mass spectrometry (Py-GC-MS) by Greg Smith, clearly displays peaks for cyclohexanone (ketone resin) monomer and for azelaic, palmitic, and stearic acid methyl esters (drying oil), verifying the presence of a drying oil **FIG. 30**.[60]

When examined under UV radiation, cross section 2 shows a thick application of fill material (layer f) with a coarse granular structure on top of the paint layers **FIG. 31**. A thin layer of retouching (layer g) lies over the fill material and a bright autofluorescent layer (i) is present over the retouching. This thin, strongly autofluorescent layer is shellac. Curiously, in this cross section the Griffin varnish was not detected on top of the shellac, as we might have expected according to Dik's statement. Further analysis with SEM-EDX showed the fill material to be composed of calcium sulfate.[61] We can also see a light blue

Fig 29
FTIR spectra of varnish from Caravaggio painting before cleaning compared to Griffin varnish and shellac. Red: varnish; blue: shellac aged six years; violet: Griffin varnish (Windsor and Newton Picture Varnish, Detroit Institute of Arts sample from the mid-1980s)

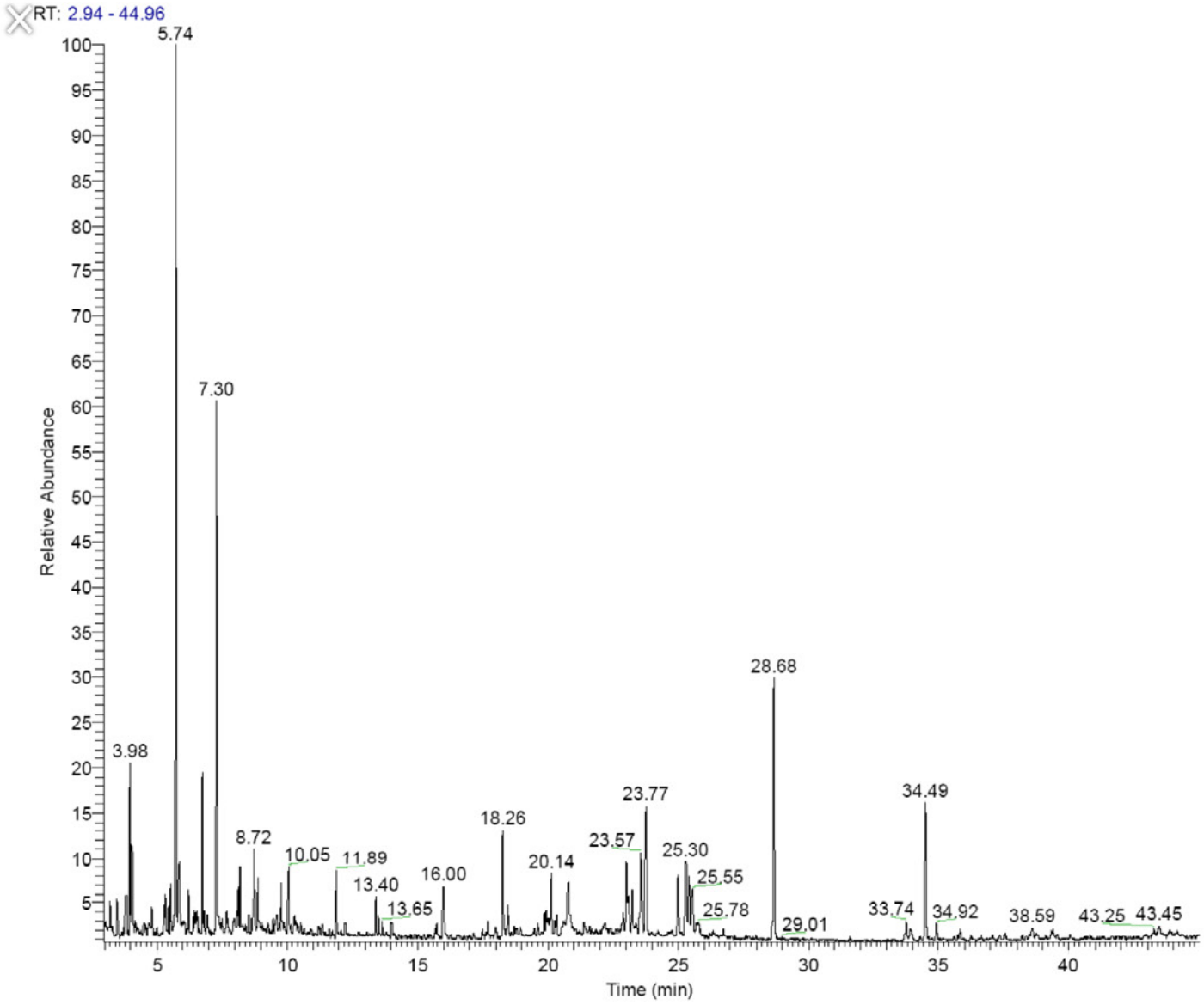

0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
Absorbance
4000
3500
3000
2500
2000
1500
1000
Wavenumbers (cm-1)

sealing layer between varnishes may be more common among European restorers.

The shellac layer was brittle, insoluble in xylene, but instantly soluble in alcohols: isopropanol and ethanol. But the coating below the shellac layer and directly over the paint was found to be softer and readily soluble in aromatic hydrocarbons, for example, xylene. Curiously, the FTIR spectrum of the lower varnish layer exhibited some peaks consistent with a ketone resin (Griffin), but also contained a considerable amount of shellac **FIG. 29**. A rare aged sample of Griffin varnish was obtained from the conservation department of the Detroit Institute of Arts. This sample, later analyzed with pyrolysis–gas chromatography–mass spectrometry (Py-GC-MS) by Greg Smith, clearly displays peaks for cyclohexanone (ketone resin) monomer and for azelaic, palmitic, and stearic acid methyl esters (drying oil), verifying the presence of a drying oil **FIG. 30**.[60]

Fig 30
Py-GC-MS spectrum for the Griffin varnish. Image: Greg Smith

When examined under UV radiation, cross section 2 shows a thick application of fill material (layer f) with a coarse granular structure on top of the paint layers **FIG. 31**. A thin layer of retouching (layer g) lies over the fill material and a bright autofluorescent layer (i) is present over the retouching. This thin, strongly autofluorescent layer is shellac. Curiously, in this cross section the Griffin varnish was not detected on top of the shellac, as we might have expected according to Dik's statement. Further analysis with SEM-EDX showed the fill material to be composed of calcium sulfate.[61] We can also see a light blue



Thermo TG-5MS (30m x 0.25mm x 0.25µm)
Pyrolysis at 600°C for 0.2 min, 3 uL TMAH
Temperature program: 60°C for 2 min; 8°C/min to 150°C; 3°C/min to 250°C; 8°C/min to 320°C
Mass Spec Parameters: 0 – 2.5 min: 26, 27, 29,3 0 m/z; 2.5 – 60 min: 40-800 m/z

RT (min)	Peak Identity
3.98	1,3,6-heptatriene
4.05	cyclopentanone
5.74	cyclohexanone
8.72	2-methylphenol
16.00	suberic acid, dimethyl ester
18.26	azelaic acid, dimethyl ester
28.68	hexadecanoic acid, methyl ester (palmitic acid methyl ester)
34.49	octadecanoic acid, methyl ester (stearic acid methyl ester)

sealing layer between varnishes may be more common among European restorers.

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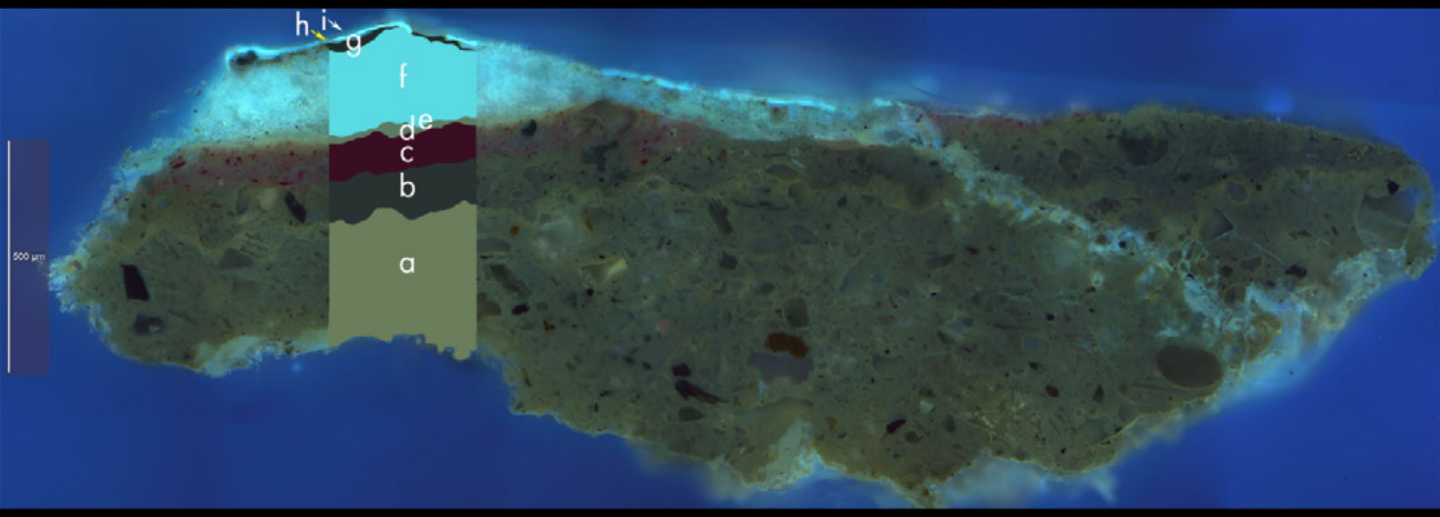
Fig 31
Cross section 2 under UV radiation

When examined under UV radiation, cross section 2 shows a thick application of fill material (layer f) with a coarse granular structure on top of the paint layers **FIG. 31**. A thin layer of retouching (layer g) lies over the fill material and a bright autofluorescent layer (i) is present over the retouching. This thin, strongly autofluorescent layer is shellac. Curiously, in this cross section the Griffin varnish was not detected on top of the shellac, as we might have expected according to Dik's statement. Further analysis with SEM-EDX showed the fill material to be composed of calcium sulfate.[61] We can also see a light blue


h
i
g
f
e
d
c
b
a
500 µm

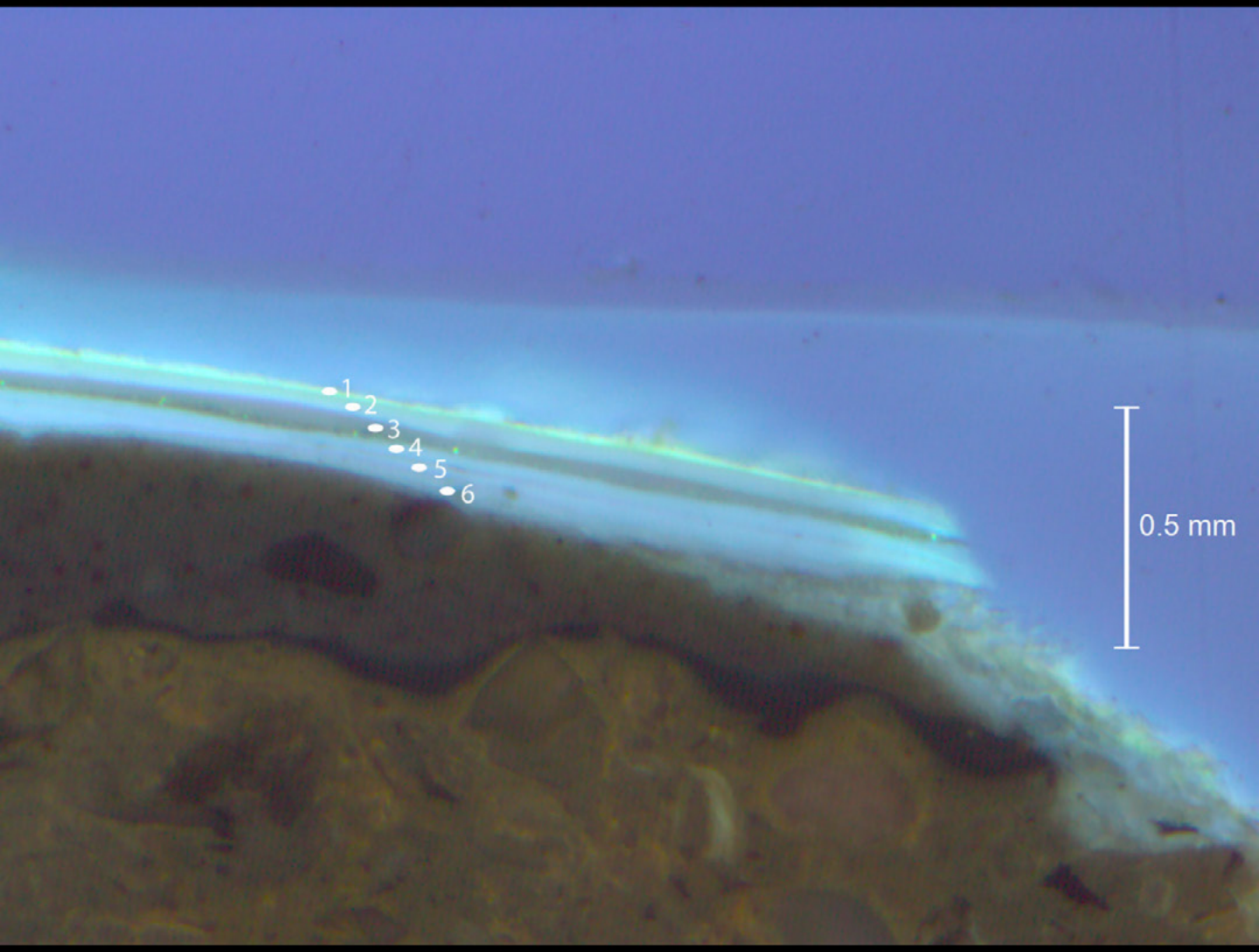
autofluorescing varnish running deep into a fracture in both the ground and paint layers.

In the UV image in cross section 4 we see a greater differentiation of the surface coatings, with four distinct applications of varnish directly over the paint, followed by a thin pigment- containing layer, a clear layer, and finally the dense autofluorescent layer at the top **FIG. 32**. Curiously, the presence of a synthetic ketone resin on top of the shellac (a natural resin) was not found in the cross sections, even when encapsulated in an acrylic resin to prevent the possibility of the embedding medium dissolving the ketone resin.[62] Light scrapings of the surface varnish from different areas analyzed with FTIR also failed to identify the presence of a ketone top layer. This contradicts Dik's statement in Merrill's questionnaire that the final varnish was composed of Griffin. However, according to the conservation records, in an attempt to remove bloom Merrill sprayed the entire painting with xylene. The sprayed application may possibly have solubilized the top Griffin layer, but its removal was not documented in the 1976 treatment log.

Fig 32
Cross section 4 showing multiple layers of varnish, UV radiation

Previous retouching from 1974 was somewhat muddled in the areas where complex tears run through the faces of the soldier and the old woman. A spatter technique was even used around the edges and in areas where the retouching was most concentrated.

A one-inch-wide continuous band of filling and retouching around the perimeter buried the torn edges of original canvas and islands of Caravaggio's paint. The

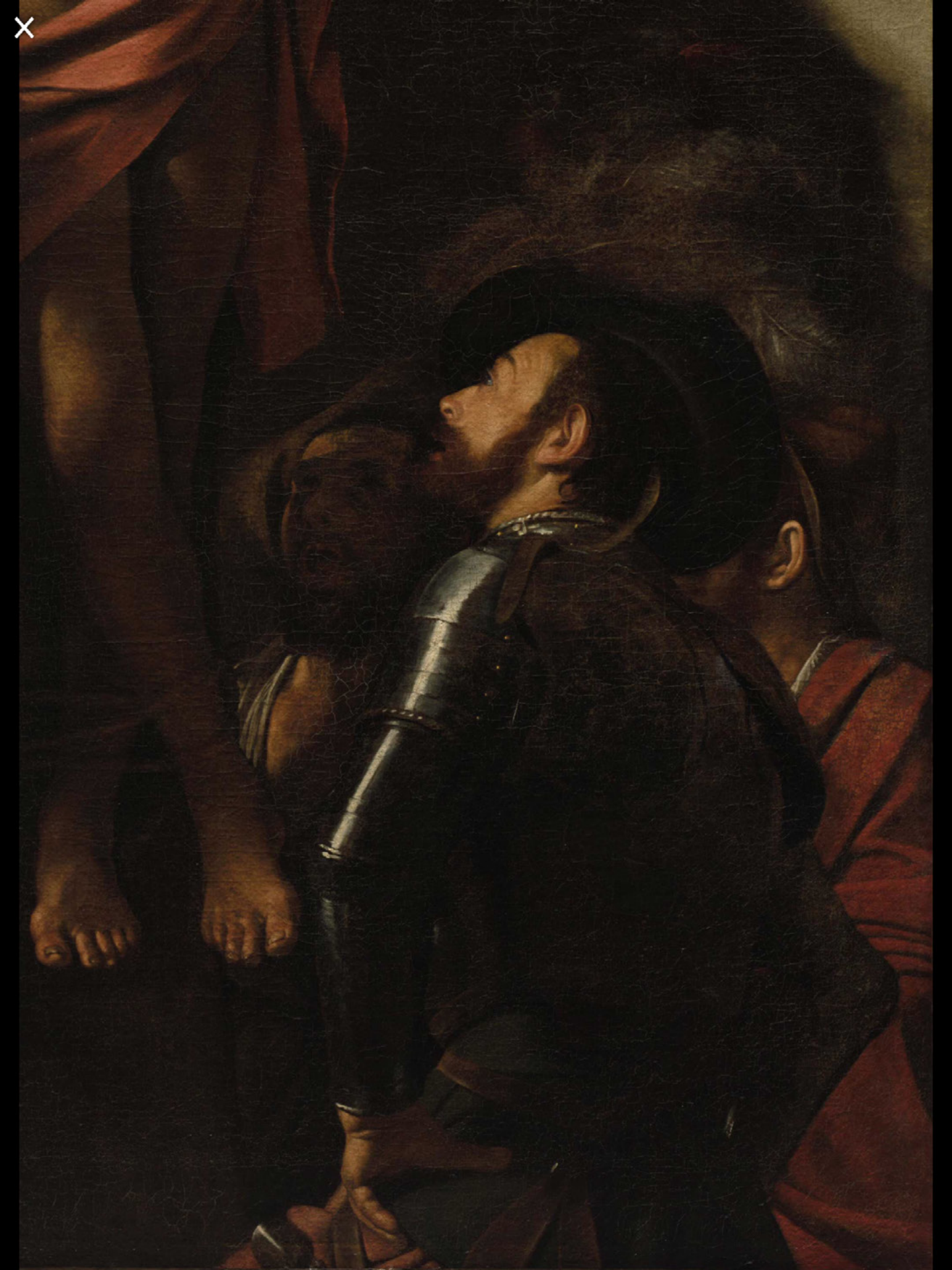

1
2
3
4
5
6
0.5 mm

surfaces of these broken islands of paint are actually in rather good condition. Removal of the band of retouching allowed recovery of much of the perimeter, which was then reintegrated with inpainting.

Cleaning Tests

As mentioned, the recent program of examination and analysis primarily sought to establish possible causes for the poor legibility throughout the painting, and especially in a number of key passages. The painting's lower right quadrant was representative of problems that appeared to be linked to the 1974 restoration **FIG. 33**. This quadrant showed six prominent condition problems: lack of legibility in the feathers of the hat; solid, opaque repainting of the hat; severe cracking in the varnish, most visible in the darker passages; opaque microcracking in the red garment; very poor legibility throughout the armor; and, as previously described, a one-inch-wide overpainted brown border covering a very damaged edge. The goal was to determine the degree to which these aesthetic limitations were caused by previous restoration treatments, and if they could be successfully reversed with a new conservation treatment. The problem of poor saturation provided by the varnish layer appeared to be similar to Merrill's description in 1976, though the coatings were likely even more deteriorated. Preliminary cleaning tests indicated that a relatively mild solvent combination of equal proportions of isopropanol and isooctane could remove the coatings. After several

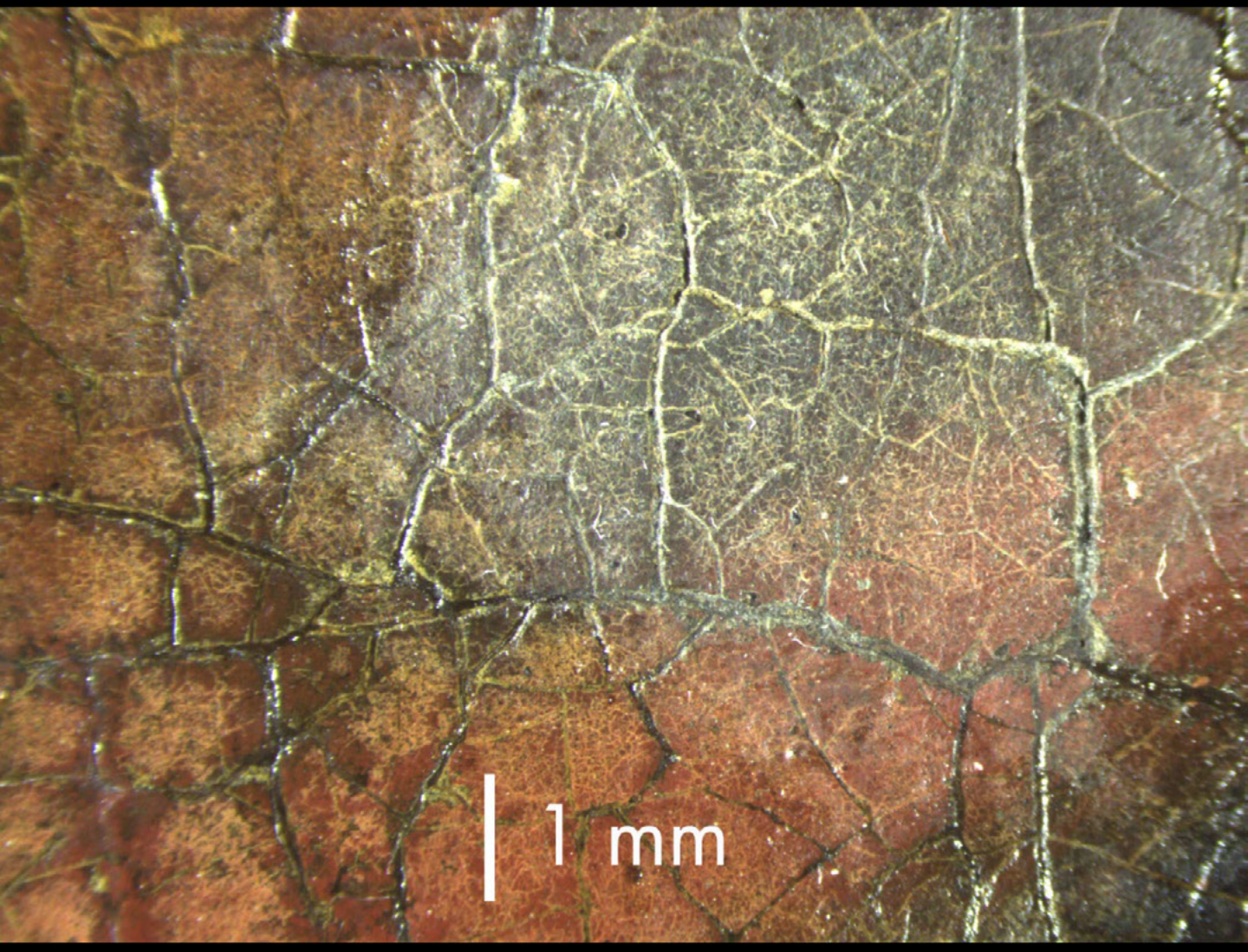
Fig 33
Lower right quadrant with aesthetic issues



applications, the top layer of varnish began to swell and was cleared away. Another series of applications began to slowly break down the underlying varnish until it was almost entirely removed. Traces of residual varnish were removed with xylene. The xylene was likely solubilizing some of the components from the first application of Griffin varnish, which would be soluble in aromatic hydrocarbons. However, further testing confirmed that repeated applications of the isopropanol and isooctane mixture safely removed both coatings, ruling out the need for an aromatic solvent.

Fig 34
Saturation of shattered surface and microfissures

After complete removal of the test area's varnish coatings, the paint surface had a shattered, washed-out or blanched appearance, as if a portion of the binding media had been extracted from the paint layer **FIG. 34**. However, closer examination determined that the blanched appearance had more to do with the presence of microscopic cracking or extremely fine microfissures that had developed in the paint layer. It seemed unlikely that a thickly applied varnish would be able to flow into these microfissures. To test this idea, a rather viscous Galdehyde resin solution was applied in a slow evaporating hydrocarbon solvent and allowed to dry.[63] The varnish penetrated only slightly, poorly saturating the microfissures. However, when the same area was brushed with 10% varnish (Regalrez® 1094) in odorless mineral spirits, an acceptable amount of saturation resulted **FIG. 35**.[64] This indicated that the paint layer could be difficult to saturate with a viscous varnish and would require quite a dilute low-molecular-weight resin to achieve proper saturation.


1 mm

applications, the top layer of varnish began to swell and was cleared away. Another series of applications began to slowly break down the underlying varnish until it was almost entirely removed. Traces of residual varnish were removed with xylene. The xylene was likely solubilizing some of the components from the first application of Griffin varnish, which would be soluble in aromatic hydrocarbons. However, further testing confirmed that repeated applications of the isopropanol and isooctane mixture safely removed both coatings, ruling out the need for an aromatic solvent.

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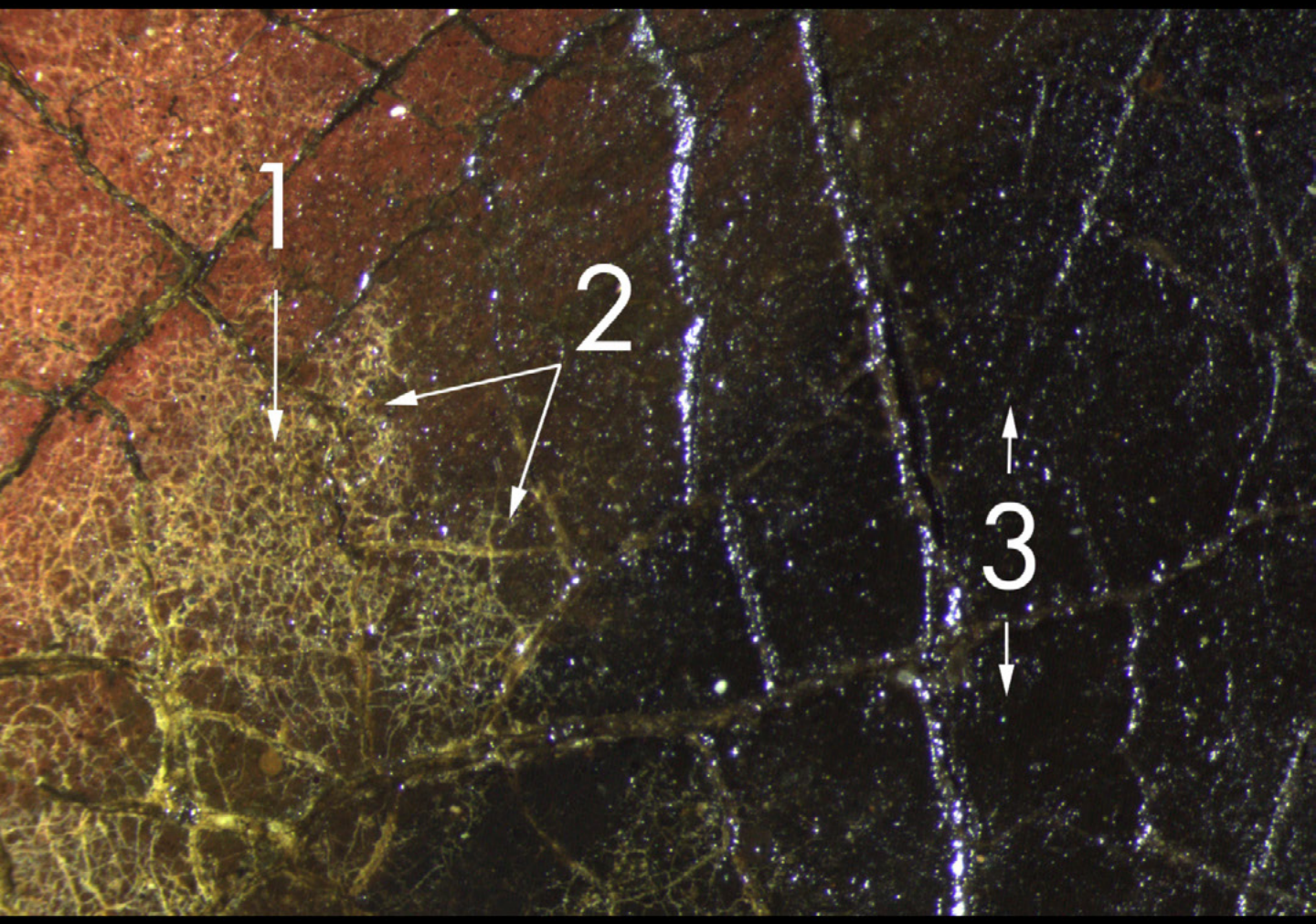
Fig 35
Shattered surface of paint layer after the varnish and old retouching were removed. Left to right: (1) Before the removal of 1974 varnish and underlying residue; (2) underlying varnish residues blocking saturation left behind from 1974 treatment; (3) after the removal of 1974 varnish and resaturation with new varnish


1
2
3

Technical Imaging: Ultraviolet Irradiation, Before Cleaning

Inspection with UV irradiation is one of the mainstays of paintings conservation. Many artist and restoration materials produce a unique autofluorescence in the presence of UV radiation. In UV-induced visible fluorescence photography, the camera records the visible light or radiation emitted from the painting.[65]

Typically, natural resin varnishes such as dammar or mastic exhibit a visible greenish fluorescence when irradiated with UV wavelengths. In the case of the *Crucifixion of Saint Andrew*, which was documented as having a multilayered varnish structure, UV irradiation induced an opaque fluorescent appearance, as seen in the UV photograph before treatment **FIG. 36**. The retouching paint, however, absorbs more of the UV, producing a darker gray-violet color. This allows calculation of the amount and location of prior retouching that occurred over the painting. However, this calculation is not always reliable, as the strongly autofluorescing varnish layers can mask any underlying retouching.

Fig 36
Before treatment, UV radiation

The UV image of the painting before treatment revealed areas of retouching that addressed the tears, losses, and paint abrasions. The soldier's hat, beard, and armor showed heavy retouching. A fair amount of retouching reduced the effects of the emerging pentimento in the elderly woman's goiter. A minor amount of more refined retouching was scattered throughout the entire painting, mostly to compensate for

losses associated with the cracking. All of this retouching was sandwiched between the underlying Griffin varnish and the shellac layer on top as described by Dik and verified by FTIR. Typically, unbleached shellac has a unique orange fluorescence. However, bleached shellac emits a light blue fluorescence consistent with the type seen here in the cross sections and UV images before treatment. The underlying Griffin varnish also emitted a rather intense induced fluorescence, but more of a blue-violet hue, discovered during the initial cleaning tests.

Looking past the most obvious large, dark blemishes and dashes of retouching are areas of faintly scumbled retouching. In these passages, Dik applied glazes of Griffin varnish mixed with oil paint to broadly tone back more concentrated areas of abrasion and heavy cracking. Because the scumbled oil retouchings contained large amounts of fluorescing Griffin varnish, they were less detectable with UV, merging with the fluorescence produced by the underlying Griffin varnish and shellac layers.

Fig 37
After treatment, UV radiation

Ultraviolet Irradiation, After Treatment

As part of the documentation process, a series of UV photographs were taken after treatment **FIG. 37**. The primary goal was to record the inpainting that appears dark violet, as both the pigments and aldehyde inpainting medium absorb the UV light. Traces of the Griffin varnish and shellac are still visible, fluorescing a light blue color. Areas where the light blue fluorescence is more concentrated reveal excess

amounts of previous varnish, though these areas appeared relatively clear under daylight conditions. One of the most interesting features of the UV photographs after treatment is the prominent milky light green fluorescence of the saint's drapery and folds in the garment of the figure on the right. The interpretation of UV photographs is not always straightforward due to lighting conditions, camera settings, filter combinations, and digital processing. However, the localized, opaque light green fluorescence is not an aberration caused by improper UV lighting controls.[66] Cross sections later confirmed that these areas of unusual UV fluorescence are the result of a medium-rich, autofluorescing paint binder as seen in cross sections 15, 16 and 17.

End Notes

58. "Statement by Jan Dik." According to Mark Gottsegen, Griffin picture varnish "is a ketone resin solution in mineral spirits"; Gottsegen, *The Painter's Handbook* (New York: Watson-Guptill, 1993), 259. According to Gottsegen, James Hamm, professor of painting conservation at the State University of New York, Buffalo, reports in a private conversation that Griffin also contained some type of oil used as a plasticizer.
59. A resinous substance secreted by a scale insect (*Laccifer lacca*) and used chiefly in the form of shellac.
60. The Griffin varnish sample from the Detroit Institute of Arts was analyzed by Py-GC-MS using tetramethylammonium hydroxide (TMAH) derivatizing agent.
61. See overlapping elemental maps of sulfur and calcium of fill material for cross section 2.
62. Cross section 2 was coated first with diluted emulsion polymer (Rhoplex™ M200), then embedded in polyester resin (Bio-Plastic™).
63. Galdehyde resin solution is composed of Laropal® A 81 (a low-molecular-weight urea aldehyde resin) in a petroleum distillate mixture. Hereafter: Laropal.
64. Regalrez® 1094 is "100% hydrogenated oligomers of styrene and alpha-methyl styrene." See Jill Whitten et al., "Low Molecular Weight Varnishes," in *Painting Conservation Catalog*, vol. 1, *Varnishes and Surface Coatings*, comp. Wendy Samet (Washington: Paintings Specialty Group of the American Institute for Conservation of Historic and Artistic Works, 1998), 109.

65. UV lamp source: Broncolor® Unilight 1600 lamp modified with a quartz glass inner dome designed to pass UV wavelengths and Broncolor® UV attachment that lets UV-A radiation and a small portion of UV-B in the range of 300–315 nm pass through. Camera: Sinar eXact view camera modified with a Kodak Wratten 2E filter and Kodak infrared cut-off filter no. 304.
66. The interpretation of the UV photograph after treatment was in consultation with Jiuan-Jiuan Chen, professor and imaging specialist in Buffalo State College's art conservation program.
67. One gram of 98% triammonium citrate acid dissolved in 100 ml of deionized water buffered with ammonium hydroxide to a pH of 6.5.

Removal of Old Retouchings and Varnish

First, the grime layer was removed with swabs moistened with a 1% solution of triammonium citrate.[67] Then varnish layers were gradually reduced with cotton swabs dipped in a one-to-one mixture of isopropanol and isooctane. Three or four applications of this solvent mixture removed nearly all of the top, yellowed shellac portion. Next, the underlying Griffin varnish began to swell, creating a fine granulated appearance. Clearly, this mixture was operating on the edge of the solubility window for the underlying Griffin varnish, which also contained a small amount of drying oil.[68] Once the solvent had evaporated, the granulated particles of the Griffin varnish were removed with a soft silicone brush. This semidry method of varnish removal allowed the Griffin varnish to be crumbled off the paint surface without the use of more polar solvent mixtures.[69] This technique proved extremely useful in coaxing the thick, fractured varnish out of the deep cracks **FIG. 38.**

Fig 38
Varnish removal

From the beginning there was some difficulty in predicting the exact amount of retouching present below the bright, opaque autofluorescence of the varnish coatings. UV examination revealed two layers of retouching, present between the top and lower layers, that generally corresponded to areas of damage associated with the canvas inserts and tears. However, as the cleaning proceeded, it

18

became clear that earlier layers of retouching were not consistently visible with UV irradiation, due to the presence of an autofluorescing binder (Griffin varnish) in the retouching. This retouching tended to be quite thick and somewhat transparent, and was often applied over large passages as a glaze to reduce the effects of abrasions caused by centuries-old cleaning. Retouching also masked areas where a white fill material containing calcium sulfate and hide glue had been intentionally applied into the cracks, likely when the lining was attached. During removal of the varnish coatings and retouching in the area of the saint's legs, red drapery, and surrounding background, it became clearer that an earlier intervention intended to fill the cracks. This fill material was deeply lodged in the crack structures that continued to fracture over time, leaving part of the fill clinging to either edge of the wide cracks. Removing the deeply embedded fill material from the cracks was not possible without harming the ground and paint layer, so it was left in place to be addressed later with inpainting. The stark contrast between the white fill material and the painting's ground layer was extremely distracting. To block out the intensity of the white fills against the darker paint, previous restorers had retouched these passages in wide swaths.

Removal of the varnish coatings led to the discovery that fills in the areas of the tears and inserts were selectively coated with a thick layer of drying oil. Fills are commonly sealed to prevent the retouching from becoming matte over

time, as the medium tends to be drawn into the porous, absorbent fill material. A large percentage of the fill material covered original paint, especially along the edges. In these areas, the drying oil was first removed mechanically with a scalpel, allowing the underlying fill material to be reduced with cotton swabs moistened with distilled water. Removal of this overlapping fill material recovered key passages of original paint, reducing the amount of inpainting required in the tears, and in the case of the edges, exposed small islands of intact original paint that provided a more accurate basis for reconstruction with inpainting. The tear running through the soldier's eye was particularly unfortunate and probably intentional. However, the removal of excess fill material revealed a small fragment of the eye's original highlight. This fortuitous discovery allowed for a more accurate placement of the sclera, discussed in greater detail in the inpainting section.

As the old coatings were being removed, a thin layer of Laropal varnish was applied by brush to assess the effectiveness of the cleaning. Dilute Regalrez varnish effectively saturated microfissures in the cleaning test areas, but produced an uneven surface gloss over larger areas. Early in the cleaning, therefore, a number of other varnishes were tested for their ability to saturate the fractured and porous paint surface. Side-by-side tests found that a fairly dilute brushed application of Laropal varnish produced good saturation and was similar in gloss to dilute applications of more traditional natural resin varnishes, such as 10% mastic

resin or 15% dammar resin in turpentine. Based on Laropal's significantly better aging properties compared to those traditional varnishes, it was chosen as both working varnish and final varnish. Therefore, residues inevitably left behind from removing the working varnish would be completely compatible with the first critical saturating application of varnish. **FIGURE 39** shows the painting after cleaning.

Fig 39
After cleaning

End Notes

68. The aged sample of Griffin varnish from the Detroit Institute of Arts was analyzed with FTIR. The spectra did not indicate the presence of oil, likely due to its low concentration. An oil component was later detected with Py-GC-MS in the presence of TMAH. See also note 58: James Hamm mentioned that after it was known that Griffin contained a small amount of oil, many conservators abandoned its use as a picture varnish.
69. Solvent combinations that included a greater proportion of isopropanol or the addition of ethanol improved the dissolution, but also tended to drive the varnish coatings into the cracked and porous paint surface.

Filling Losses in the Paint Layer

The next critical step in the conservation treatment was to create the proper texture over the preexisting fills. A number of solutions were tested, including the casting of silicone molds of the paint surface for imprinting textures. In the end, the best technique was careful application of the fill material in liquid form to each area of loss. Applied using a small brush, diluted Modostuc paste, which is reversible in water, best emulated the gritty structure of areas of exposed original ground and paint and could easily be carved to connect crack structures.[70] Once the old losses and preexisting fill materials were properly leveled and textured to imitate the surrounding paint, a layer of inpainting medium composed of powdered pigments and polyvinyl acetate (PVA) resin[71] was used to cover the Modostuc and provide a foundation for the next phase of comprehensive inpainting. This PVA foundation layer was mixed to closely match the color of the original ground and the sheen of the unvarnished original paint by adding dry powdered pigments. This step, sometimes referred to as blocking-in, immediately began to visually neutralize the losses, causing them to recede or meld into the overall dark tonality of the underlying ground layer **FIG. 40**.

Fig 40
After blocking-in

Inpainting and Reintegration

After the filling and blocking-in phase, an isolating varnish composed of Laropal resin diluted in solvents was brushed over the entire painting to provide uniformly even saturation.[72] The Laropal varnish produced a relatively soft, satinlike sheen to the original paint and the foundation layer over the losses. As in previous test areas, the Laropal varnish also effectively penetrated the microfissures, providing the deep and rich saturation the painting so desperately required.

The next step involved comprehensive inpainting over areas of abraded original paint and textured losses. Conservation pigments in a wide range, especially finely ground transparent earth pigments used in conjunction with bone black, were essential in reproducing the deep, rich tonality in the darkest passages, and the warmth of Cremnitz (lead) white pigment provided a good match to the aged original lead white paint.[73] The underlying ground tone of the foundation layer created an effective foil for the layered fine dots and vertical dashes emulating the worn appearance of the original paint layers. This inpainting technique was particularly useful in areas where Caravaggio had applied light colors over the darker ground as the denser areas of inpainting became warmer and more opaque, while the same pigment applied in thinner layers, which allowed the darker ground to emerge, took on a cooler tonality. Likewise, inpainting in the darker passages of the shadows and

background was executed with thin, dark translucent tones, allowing the dark tones of the ground color to emerge.

One of the more challenging aspects of the inpainting was reconstructing the soldier's eye. Caravaggio placed the soldier's eye in nearly complete profile, probably to emphasize his surprised expression. The three known copies of the painting depict the soldier's eye with nearly the same exaggerated profile, and both the Back-Vega and Dijon paintings share a pronounced diagonal catchlight. During cleaning, the fortuitous recovery of the eye's original catchlight guided the reconstruction of the surrounding sclera, or white of the eye. Neither the Back-Vega nor the Dijon painting possesses the level of facial detail of the soldier in the Cleveland painting. Both paintings, however, were indispensable guides for the eye's most logical reconstruction in the Cleveland picture, helping to position the iris and eyelids. After complete removal of the excess fill material and old retouching from the soldier's face, another delicate, original highlight was discovered along the bridge of the nose. The recovery of this important highlight, which likely served to separate the dark iris and black pupil from the black hat, helped to better define the original spatial plane occupied by the nose, allowing the eye to sit within the eye socket.

Another problematic area that required a sensitive reconstruction was the soldier's open mouth, heavily abraded from an earlier restoration. Clearly this damage occurred well before the 1974 restoration, based on a

black-and-white photograph taken by Dik after cleaning and before retouching **FIG. 41**. Each of the copies shows the soldier with an open mouth, again to emphasize his amazed expression. Even though the thin glazes used to define the mouth, moustache, and beard were largely missing, a small amount of the original paint could be seen within the fine interstices of the lighter underlying abbozzo strokes. The missing glazes were gradually reintegrated in several stages, inpainting only the raised ridges of abrasion, exposing the abbozzo. During the later stages of inpainting, the rudimentary form of the soldier's open mouth eventually began to emerge. The final shapes of the open mouth, moustache, and beard were reconstructed, extrapolating directly from original surviving fragmentary glaze, using the less nuanced copies as only a general reference.[74]

Fig 41
After Jan Dik's cleaning and before retouching in 1974

Equally challenging was the reconstruction of the soldier's plume and broad-brimmed hat—among the painting's most damaged passages. In the hat, the darkest strokes of original paint had been almost entirely eroded away by a harsh overcleaning that occurred sometime before 1974. This aggressive cleaning exposed a considerable amount of the underlying ground layer. The plume also suffered from past overcleaning, but survived in better condition because some of the lightly colored wispy strokes of the feather were painted with lead white, which is much less vulnerable to cleaning solvents. Areas throughout the plume also had a muddled appearance caused by residual varnishes. Once these areas were cleared of those old

residues and saturated with Laropal varnish, a significant amount of detail emerged, allowing a sensitive reconstruction of the plume with a moderate amount of inpainting. However, the expansive losses in the darkest black paint, which define the underside of the circular edge of the tipped hat, required a major amount of reconstruction. This extremely critical passage in the painting places the soldier in front of the figure on the extreme right, whose face is partially blocked by the hat. The Dijon and Back-Vega paintings offered some general guidance, but the Dijon painting's rather crude depiction of this passage provided little insight into any nuances that may have been present in the Cleveland painting, and the photographs of the Beck-Vega after cleaning revealed a significant amount of old damage in the same area.[75]

Upon close inspection, tiny remnants of surviving deep black original paint scattered within this area of loss in the Cleveland painting provided faint clues for color matching. Therefore, the reconstruction strategy here was to meticulously reproduce or duplicate these specks of original paint with minute dots of inpainting until a dark translucent field emerged that mimicked the appearance of aged, slightly abraded original paint. Gradually, after repeated passes of pointillist inpainting, the lower outside brim of the hat began to take form against the shadowed face of the figure in the lower right. However, the final shape of the lower brim created with inpainting is only a rough approximation based on the projected elliptical foreshortening seen in the other

versions and the minute clues of original paint.

The elderly woman's shawl—where a sizable loss had been repaired with a canvas insert—also required comprehensive reconstruction. The Back-Vega painting provided important information to complete a horizontal Y-shaped fold that was completely lost in the Cleveland painting **FIG. 42**. Curiously, the Dijon painting had sustained damage in the same exact area. Images of the Back-Vega during treatment confirmed that this passage was original and not altered by restoration; the images were used as a model for the reconstruction of the corresponding lost passage in the Cleveland painting.[76] As with other areas of complete loss, the inpainting was structured using fine layered dots and dashes to create subtle modulations of color and transparency, which were gradually built up over the pretextured darker foundation layer that matched the ground color. Here, too, this inpainting strategy proved to be quite successful in visually bridging the complete loss with the natural aged and cracked appearance of the surrounding original paint.

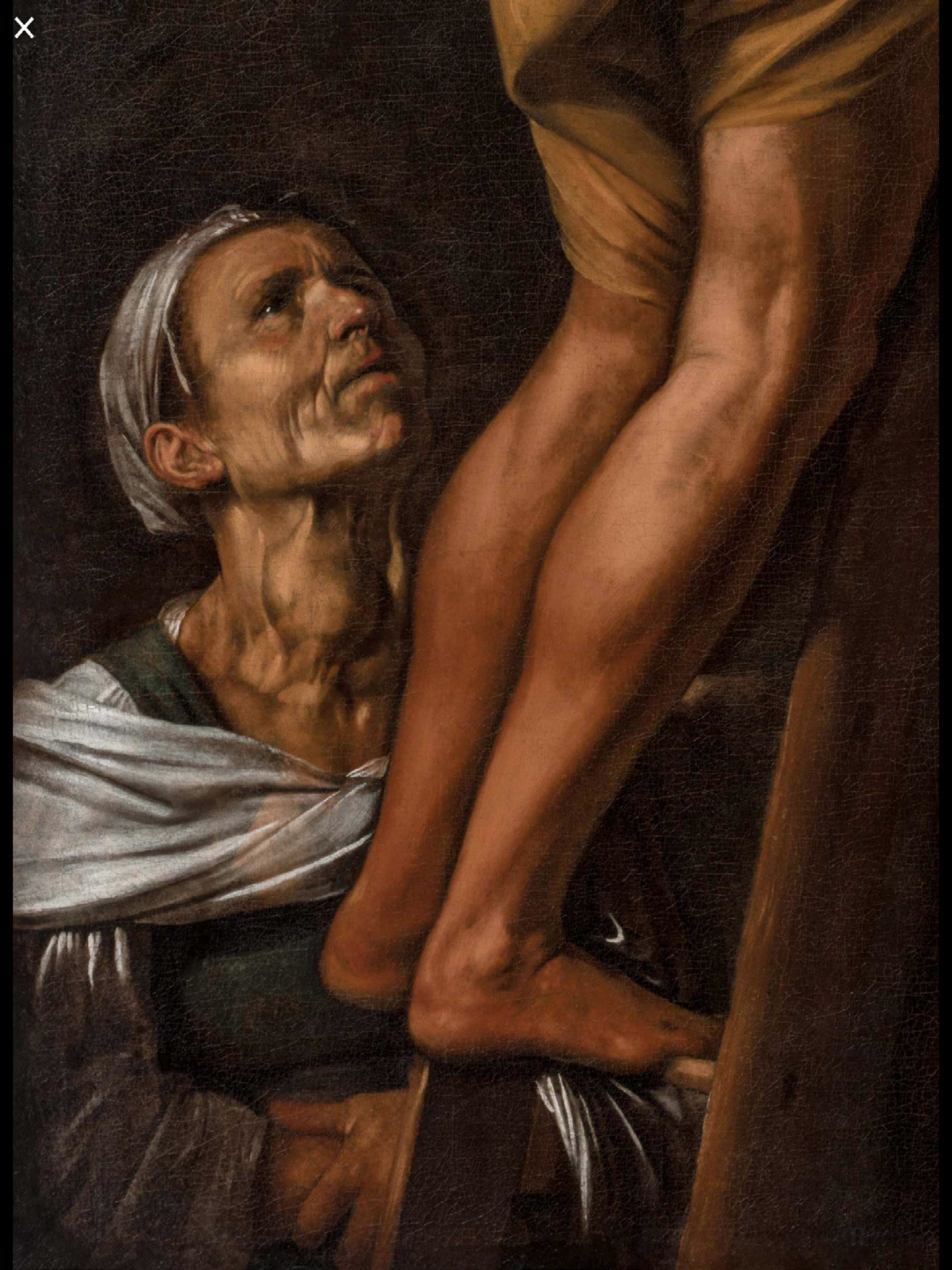
Fig 42
Detail of the Y-shaped fold in the Back-Vega painting

Another critical step was to determine the amount of inpainting required to compensate for past cleaning interventions, which accentuated the prominence of the pentimento of the first placement of the old woman's hands. There was a consensus that the 1974 restoration had reduced the degree to which the pentimento would normally have been visible had overcleaning not occurred. Furthermore, this artistic change, absent from the other versions, was an

important indication of the painting's authenticity as the original painting at the time of the acquisition. Even though it may slightly interfere with the reading of Caravaggio's final intentions, the pentimento should not be hidden. Therefore, the area was inpainted with restraint, addressing only the damage caused by cleaning abrasions, allowing the pentimento of the hands to appear as they would have through natural aging **FIG. 43.**

In some respects, the most difficult inpainting was in areas in the dark passages of the figures and background where cracking and abrasions along the top ridges of the cracks interrupted Caravaggio's extremely subtle transitions of color and form. Many of these passages were further compromised by aged white fill material lodged deep into the cracks and impossible to remove. The most challenging passages were in the saint's crossed legs, the diaphanous ropes around his legs, and the lower portion of the rough-hewn cross below his feet. While a great many losses had been filled during earlier interventions, hundreds of smaller losses required filling with proper texture. As the inpainting progressed, subtle details lost in the chaos of the cracking and abrasions began to emerge. Remarkably soft, skillfully blended contours and nuanced transitions of color used to create volume and space became increasingly evident in the saint's lower torso and drapery. Caravaggio's rapid brushwork in the background also began to reveal modulations in opacity and translucency, revealing the underlying tonality of the ground layer.

Fig 43
Pentimento after treatment



A monotonous yet extremely important aspect of the inpainting treatment was reconstructing the entire original perimeter. Though Caravaggio is known for tightly cropping his figures within the constraints of edges and corners, the arbitrarily conceived brown border further cropped the composition, nearly clipping the saint's bent index finger in the upper left corner. While the removal of the painted brown border exposed the perimeter's rough condition, it also revealed hundreds of small islands of intact original paint that extended to the extreme edge. These small yet significant pieces of original paint provided critical information needed to bridge the losses and enable an accurate and sensitive reconstruction of the painting's perimeter, extending the original painted dimensions by approximately one and a quarter inches along each edge.

As a result, the saint's index finger and the left arm of the figure on the ladder, no longer impinged by the painted border, now have sufficient space to recede into the proper spatial plane. Fragments of original paint along the edges in the lower right corner aided reconstruction of the red garment's broken edges to the painting's outside edge. And in the lower left, original fragments of the blue-green dress and white shawl of the elderly woman were used to extrapolate the continuation of the folds to the painting's bottom and left edges.

The return of the painting's sense of space, made possible by the cleaning and intensive inpainting, is perhaps one of the most transformative aspects of the conservation

treatment **FIG. 44**. The spatial effects that Caravaggio so successfully exploits in his paintings had been significantly diminished by the painting's abraded and cracked condition and previous restoration attempts. Undoubtedly, the vast number of cracks and abrasions scattered throughout the painting pushed earlier restorers to repaint over these areas. While the most recent treatment from 1974 was done with some restraint, it nevertheless employed a great deal of scumbling over nuanced details that Caravaggio used to create volume and space within and around his figures. The 2014–15 cleaning revealed the full extent of the damage, but also an amazing amount of original refined brushwork, subtle layering, and exquisite sharpening and blurring of contours.

Fig 44
After treatment

Interfering as little as possible with original paint was the primary aim of the inpainting. This required using high magnification and finely pointed brushes. Some critical areas, only an inch square in size, required many hours of concentrated work to reintegrate losses and abrasions so they melded into surrounding areas of original paint. As this process evolved, minute details once lost began to materialize. The most significant of these were gradations within darker passages and subtle but dynamic transitions between blurred and tightly crisp contours. For example, Caravaggio carefully blurs the contours of the saint's legs as they recede into darkness, but sharpens the edges of the contour to articulate the point where the quadriceps muscle of his right leg falls over the receding muscle groups. This

interplay between soft and sharp line appears throughout the painting. Caravaggio packs sharper details into the lines of the foreground soldier, while the figure to his left, farthest away in the shadows, is painted with less detail and more blending, causing him to recede.

End Notes

71. PVA conservation paints (Golden Artist Colors Inc.) modified with additional dry powdered pigments.
72. Twenty grams of dry resin (Laropal A 81) were dissolved in 100 ml of hydrocarbon solvents—a high-flash-point aromatic and a mineral spirit type (ShellSol A100/D38)—in a 1:2 ratio. Testing of slightly more dilute mixtures produced uneven surface gloss due to the surface porosity caused by areas of exposed ground and cracking.
73. Gamblin conservation colors are composed of powdered pigments ground with Laropal resin, compatible with the isolating varnish composed of the same resin.
74. Images made during treatment of the Back-Vega painting reveal that the conservator reconstructed a substantial amount of damage in the area of the soldier's mouth. Therefore, that painting did not provide particularly useful information for the reconstruction of this passage.
75. Images of the Back-Vega version during the cleaning are in Papi, *Caravaggio: The Back-Vega Crucifixion of Saint Andrew*, 59.
76. Ibid., 58–60.

Incisions and Other Primary Markings

The removal of thick varnish layers improved the textural reading of the paint layer, allowing the discovery of incisions in raking and specular light. These observations in combination with infrared and X-ray imaging executed before treatment have clarified and expanded the number of incisions throughout the painting.

In passages where a lead white abbozzo is absent, incisions are not visible in either the X-ray or infrared spectrum. However, once the thick varnish layers and restoration paint were removed, numerous incisions and markings became visible with magnification during the inpainting process. These incisions (mapped in green) are discernible only in extreme raking and specular light **FIG. 45**. An entire group of refined, delicate incisions was discovered in the soldier, marking the fine details of the armor, belt, hat, thumb, and waistcoat **FIG. 46**.

Another set of incisions appears in the shadowed figure to the immediate left of the soldier, corresponding to contours of the top of his hat and the fold in his garment. In the same figure, a straight diagonal incision is present between the edge of his eye and the soldier's chin. This incision seems to mark both the center position of the eye and the bottom of the soldier's chin.

Fig 45
Incisions mapped in green, under raking light

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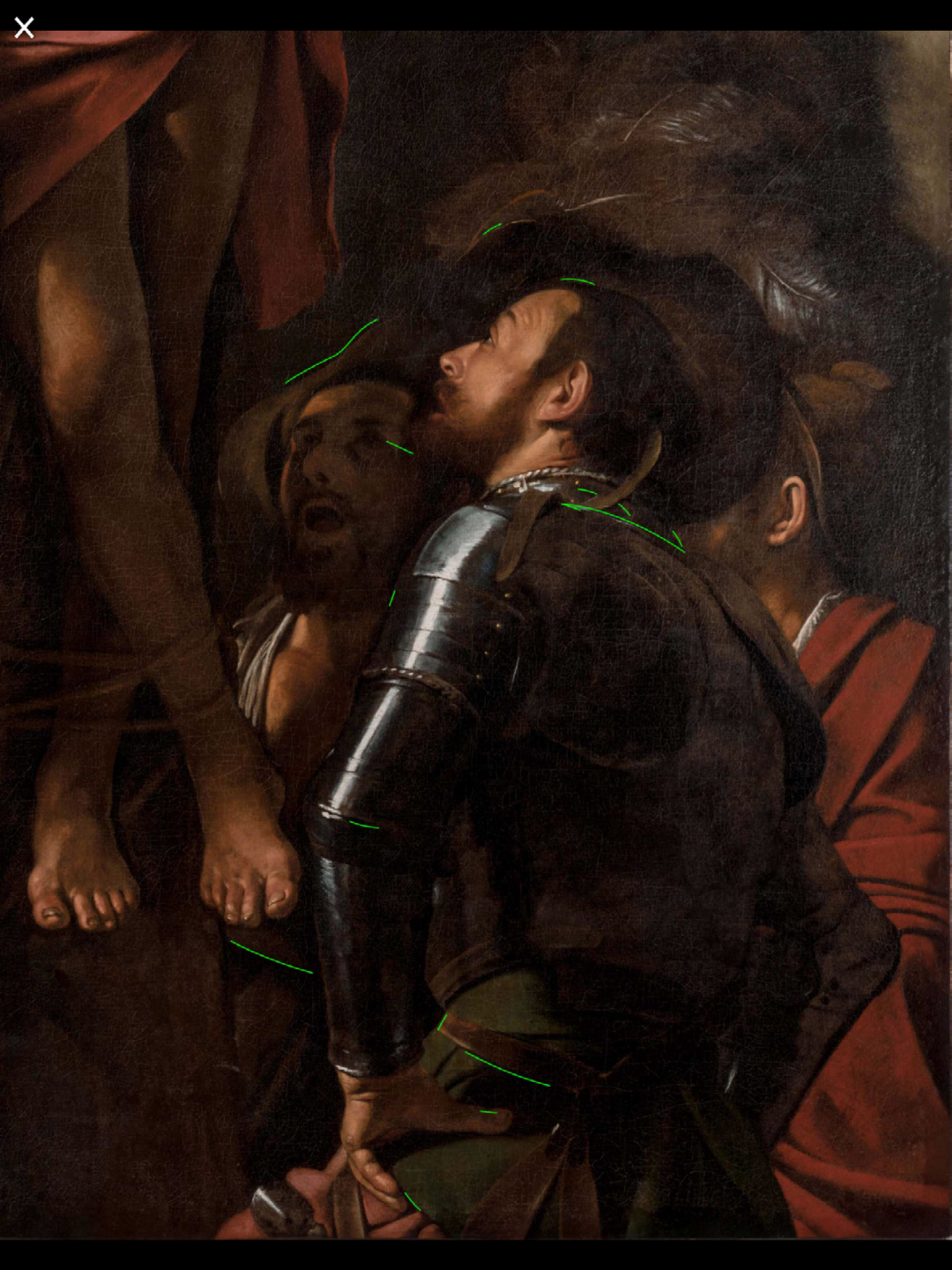
Fig 46
Refined incisions of the soldier mapped in green, under raking light



One long continuous incision designates the outside anatomical contours of the executioner on the ladder. The incision on his right side (mapped in green in fig. 45) refers only to the contour of his torso, and runs through the shadowed folds of his loosely tied shirt.

A series of short, staccato incisions in the upper left quadrant follow the top contour of the saint's right arm. Directly below his right hand, two nearly straight parallel incisions appear to mark the lower edge of the cross transept **FIG. 47.**

Fig 47
Double incision at the bottom of the cross transept

The figure on the ladder has a short, diagonal incision just to right of his head, wider and deeper than the incisions marking the figure's body contours. The fact that the top of the figure's head is closely in line with this incision suggests that it may roughly mark the height of the figure. Its deeply plowed nature suggests that it may have been made while the ground layers were still soft, quite early in the painting process **FIG. 48.**

Two straight horizontal incisions visible in X-ray and raking light, one near the bottom of the shoulder blade of the figure on the ladder and the other through his dangling sleeve, both appear to be cut with a wider stylus. The incision marking the lower shoulder blade is nearly in horizontal register with two short incisions below the ribs of the saint **FIG. 49.**

The horizontal incision of the dangling sleeve is particularly interesting because it has no apparent link to the sleeve **FIG. 50.** It does, however, bisect the center point of the

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A series of short, staccato incisions in the upper left quadrant follow the top contour of the saint's right arm. Directly below his right hand, two nearly straight parallel incisions appear to mark the lower edge of the cross transept **FIG. 47.**

Fig 48
Deep incision marking the top of the executioner's head

The figure on the ladder has a short, diagonal incision just to right of his head, wider and deeper than the incisions marking the figure's body contours. The fact that the top of the figure's head is closely in line with this incision suggests that it may roughly mark the height of the figure. Its deeply plowed nature suggests that it may have been made while the ground layers were still soft, quite early in the painting process **FIG. 48.**

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Fig 49
Horizontal incisions marking the executioner's shoulder blade and Saint Andrew's torso

Two straight horizontal incisions visible in X-ray and raking light, one near the bottom of the shoulder blade of the figure on the ladder and the other through his dangling sleeve, both appear to be cut with a wider stylus. The incision marking the lower shoulder blade is nearly in horizontal register with two short incisions below the ribs of the saint **FIG. 49.**

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The horizontal incision of the dangling sleeve is particularly interesting because it has no apparent link to the sleeve **FIG. 50.** It does, however, bisect the center point of the

Fig 50
Horizontal incision through the dangling sleeve

bent contour of the figure on the ladder, and when that horizontal line is extended, it intersects the exact vertical midpoint of the saint's body.

Primary White Markings and Finger Dabs

A number of delicately applied white lines that seem to be early markings used to define components of the soldier's armor were revealed after the cleaning. The most striking example is two short linear marks that roughly correspond to the leather strap used to hold the pauldron to the gorget **FIG. 51**. These markings, clearly applied in the painting's early stages, are now visible because of a prior harsh cleaning that removed the uppermost paint layers. Similarly, a faint white line corresponding to the lower contour defining the earlobe of the figure wearing the red garment on the right also appears to have been applied in the early stages of painting **FIG. 52**. This white line is a thin painted stroke applied directly over the ground layer and would have been resistant to aggressive cleaning solvents, which removed the more vulnerable, thinly painted darker paint at the edge of the shadow. The other most notable area of underlying white strokes can be seen adjacent to the decorative roping ornamentation in the soldier's armor **FIG. 53**. These finely brushed strokes extend from the more defined areas of the roping into the dark black paint of the armor. None of these faintly applied white strokes are clearly visible in the X-ray, which may indicate a composition other than lead white. Traces of white lines appear along contours in a number of other areas: for example, around the ropes in the upper left

Fig 51
White lines marking the leather strap

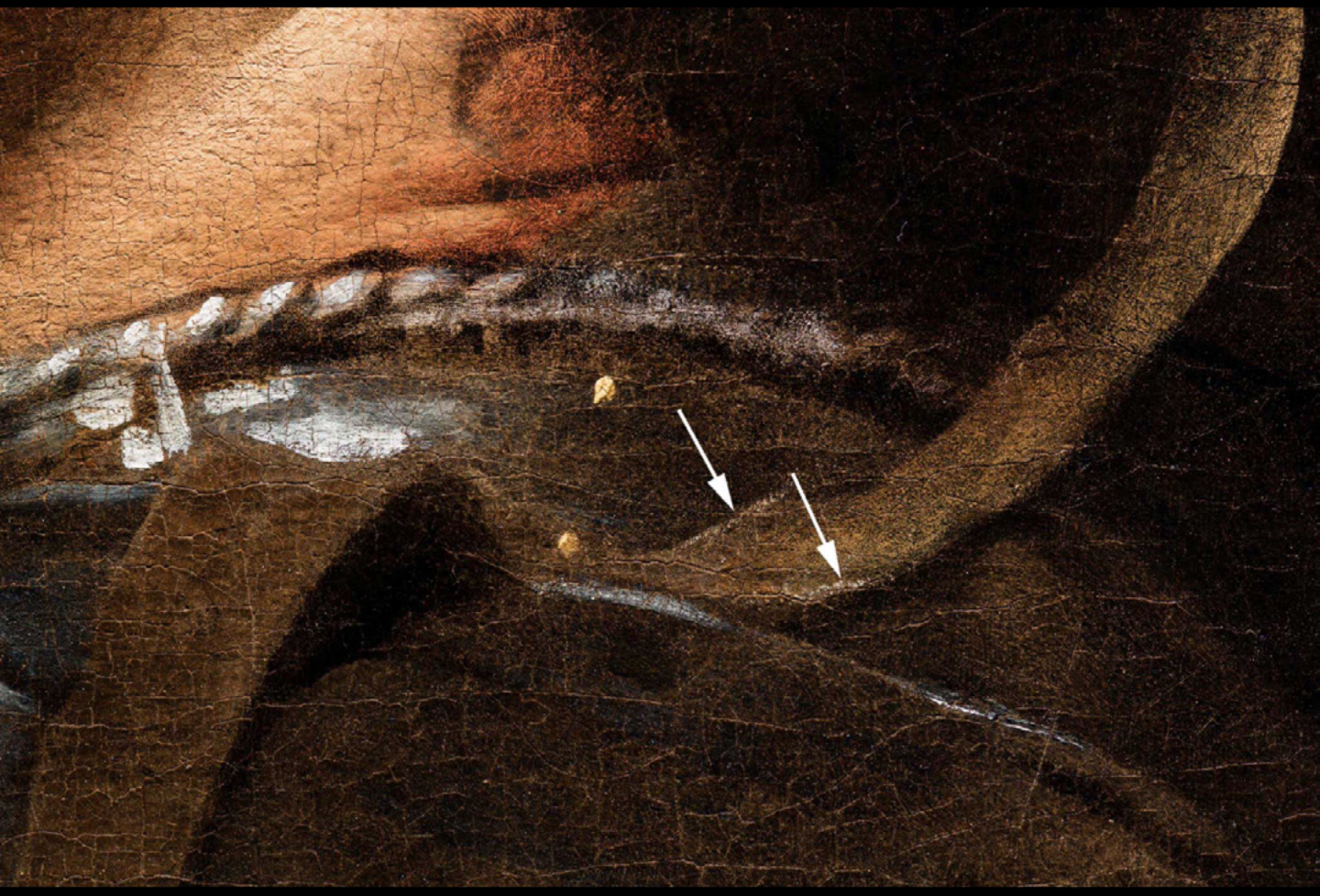

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Fig 52
White line at the outer edge of the earlobe

Primary White Markings and Finger Dabs

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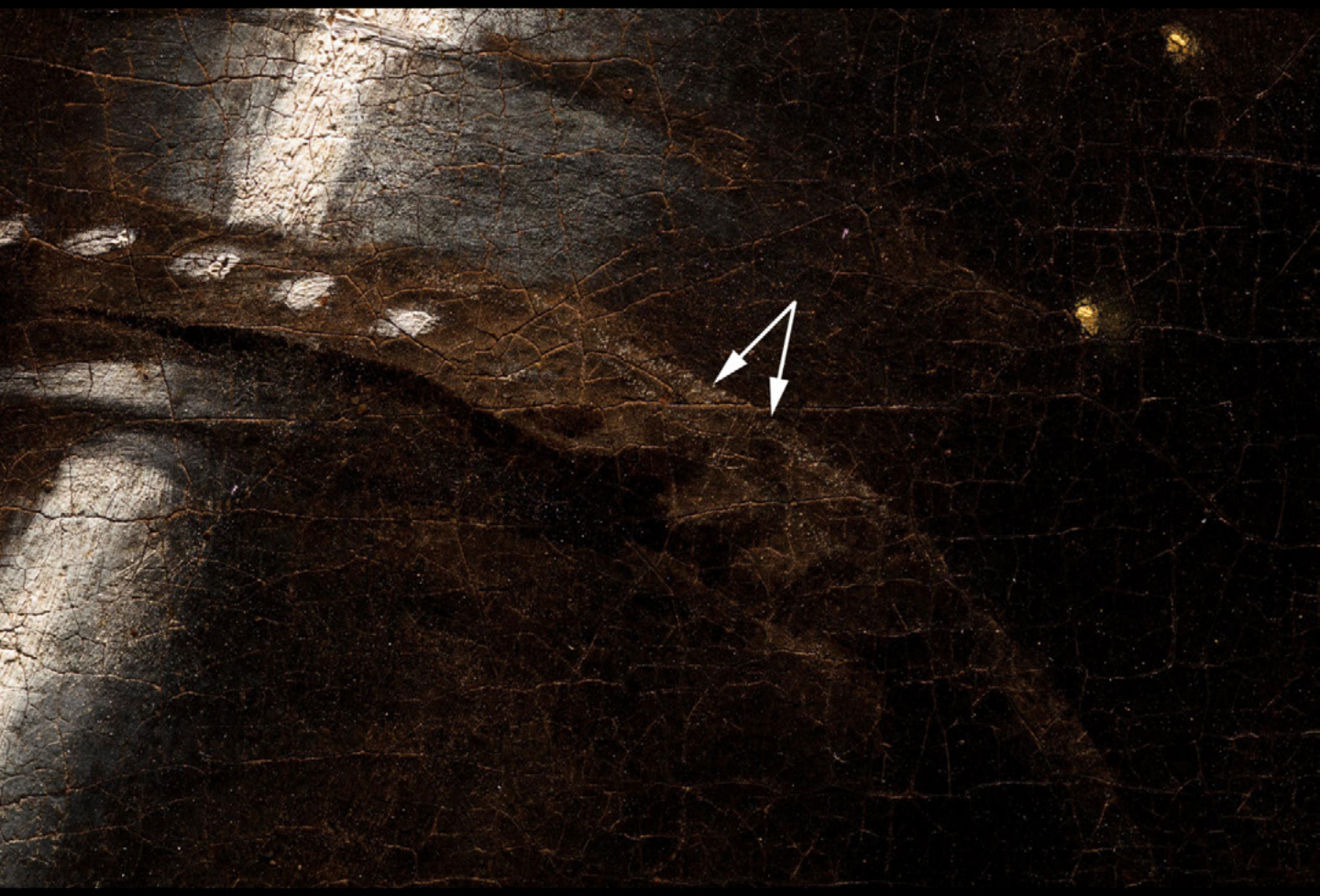
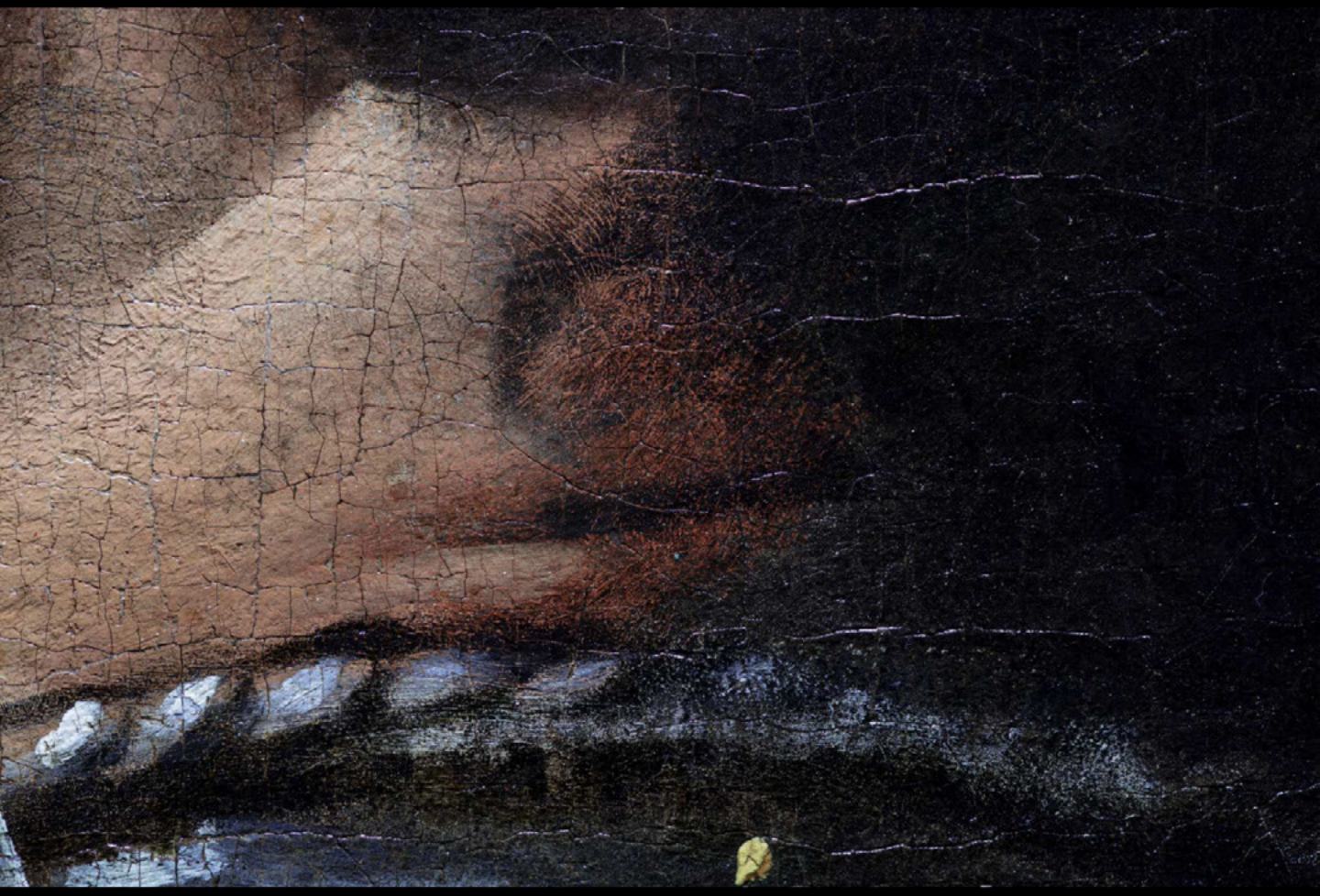
Fig 53
White lines on the soldier's armor

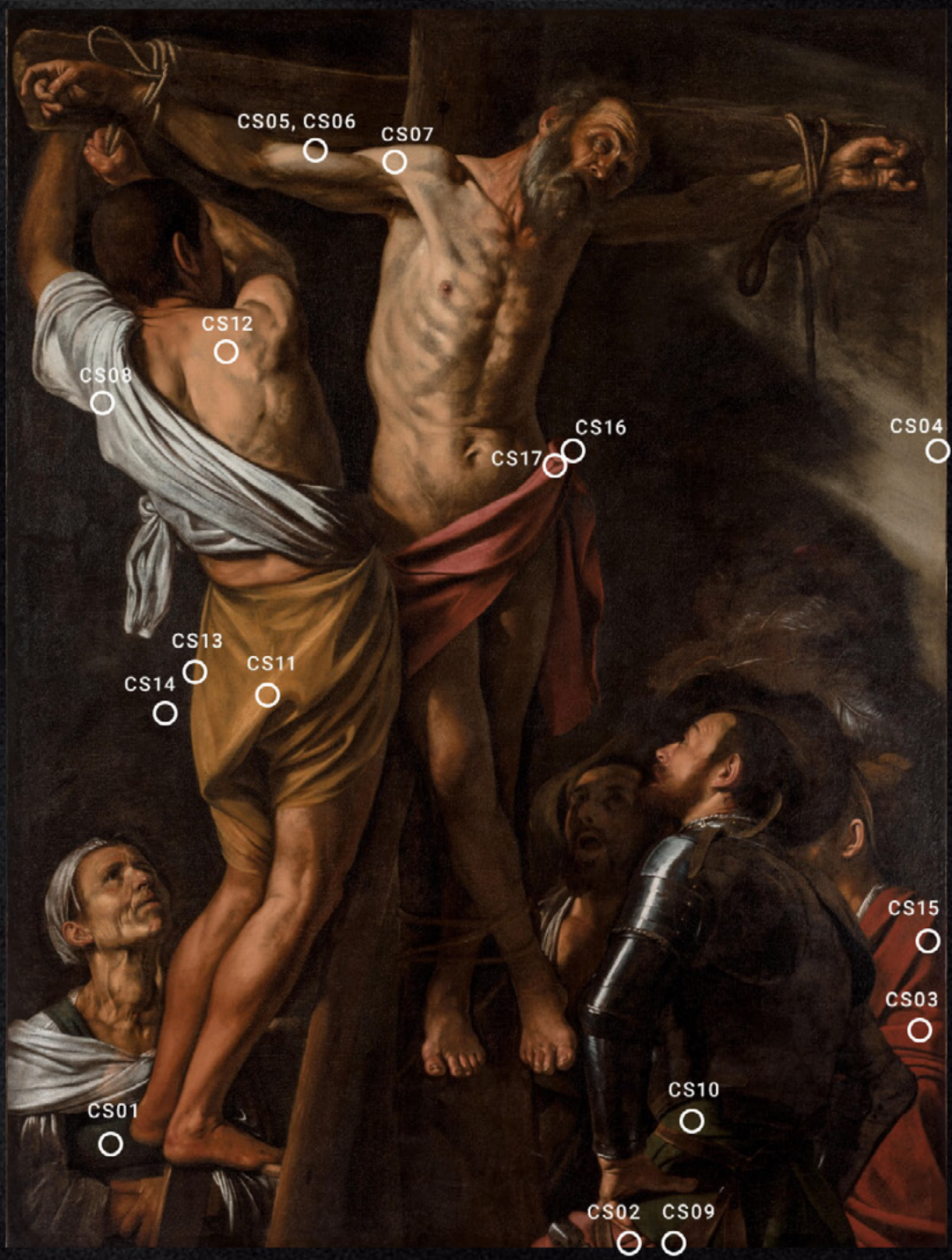


and right corners. However, these passages are even less clear, and nearly impossible to convey with a photograph. While it is unfortunate that the aggressive cleaning removed the layers of paint that would have covered these faint white strokes, their presence seems to indicate that Caravaggio also used refined white markings as early guides for certain details.

In a few areas, cleaning exposed reddish flesh-toned dabs of paint about the size and shape of a finger. These paint dabs are located along the rim of the figure's hat on the far right, on the saint's right cheek, and on the right arm of the cross transept. A possible fingerprint or brush swirl is located in the underlying paint layers of the shadow area of the soldier's neck, just below his ear **FIG. 54**. Whether the artist applied these with brush or finger remains a mystery.

Fig 54
Possible brush swirl or fingerprint just below the soldier's ear





Introduction to Analysis of Cross Sections

Introduction to Analysis of Cross Sections

Dean Yoder, in collaboration with
Gregory Smith, PhD

Seventeen samples were lifted from the painting before, during, and after treatment to conduct more in-depth analysis of the paint and ground layers. The image shows where the samples were taken. Since this type of sampling is a destructive process—requiring the complete removal of original material—samples are usually no larger than two to three millimeters and their locations strategically chosen to create as little damage as possible, while yielding the most information. These extremely small fragments give conservators and conservation scientists the opportunity to study in greater detail the stratigraphy and chemical composition of ground, paint, varnish, and restoration layers. For example, the analyses of cross-section samples 2 and 4, taken before treatment, confirmed the compositions of both the original and the restoration materials, providing an informed framework for the treatment. Both of these samples were removed from the extreme edge of the painting by inserting a scalpel blade between the original canvas and the lower ground before gently prying upward.[1] This method proved the most successful in preventing delamination of ground and paint layers during sampling.

The remaining sampling sites were located within the interior of the painted surface. Thus, these samples were removed based on their proximity to deep cracks or crack structures so that a pointed blade could be inserted down through the crack into the lower ground. The blade was then carefully lifted, prying up from the lower ground until the sample broke free. As a result, not all samples were taken cleanly; cross

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To prepare the samples for microscopic examination, the paint chips were placed sideways within an epoxy resin embedding medium and then highly polished with abrasive cloth.[2]

The samples were examined and photographed under normal light from a halogen lamp and UV irradiation using a mercury vapor source with the CMA's research microscope and a digital microscope camera.[3] SEM-EDS (scanning electron microscopy–energy-dispersive X-ray spectroscopy) and Raman spectroscopy analyses for cross sections were conducted by Gregory Smith at the conservation science laboratory at the Indianapolis Museum of Art.[4]

Note: The SEM-EDS mapping images are listed in order of atomic weight.

1. Equipment used: A carbon steel no. 11 surgical scalpel blade in conjunction with a McCrone 107-2 tungsten needle to extract and transfer the samples into a recessed block of silicone.

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2. Samples were embedded in a two-part epoxy resin (EpoxiCure®2)—except for samples 2 and 4, which were embedded in Ward's Bio-Plastic® polyester resin. Cross sections were polished with cushioned abrasive discs (Micro-Mesh™) using a Struers Dap-7 polishing machine.

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3. Equipment used: Zeiss Axioskope 2 Mat compound microscope, with halogen (H 100) and mercury vapor (HBO) radiation sources; filter set 02 (G365 excitation UV, beam splitter FT 395, emission LP 420); filter set 09 (BP 450–490, excitation blue, beam splitter FT510, emission LP515), and dark-field module D for normal light. Images were captured with a Leica DFC495 digital microscope camera with the Leica Application Suite (LAS). All of the microscope images were captured through a Corning cover glass (no. 1–1/2, 22 mm2) wetted underneath with odorless mineral spirits. Cross sections 5, 6, 8, and 9 were photographed under normal light and UV at the conservation lab at the Indianapolis Museum of Art.

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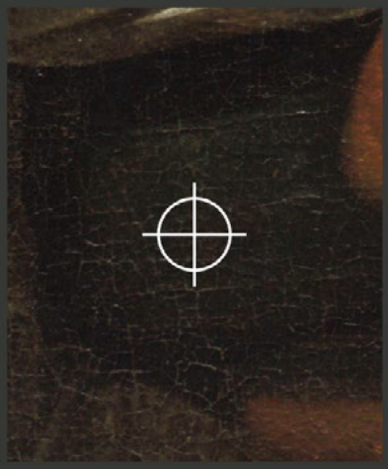
4. Elemental images of cross sections were acquired on a Zeiss Evo MA15 SEM under variable pressure conditions (40 Pa room air) using a five-segment backscattered electron detector or a Bruker Quantax 200 EDS detector. The electron beam was generally operated at a current of ~1 nA and 20 keV accelerating voltage.

Note: The isted in order of atomic weight.

Cross Section 1 (CS01)

Location: Blue-green color in the elderly woman's blouse

The sample was taken after the treatment was complete to determine the composition of the dark blue-green paint used in the elderly woman's blouse. SEM-EDS analysis was not conducted on this sample; Raman spectroscopy was able to reliably identify the pigments in question.

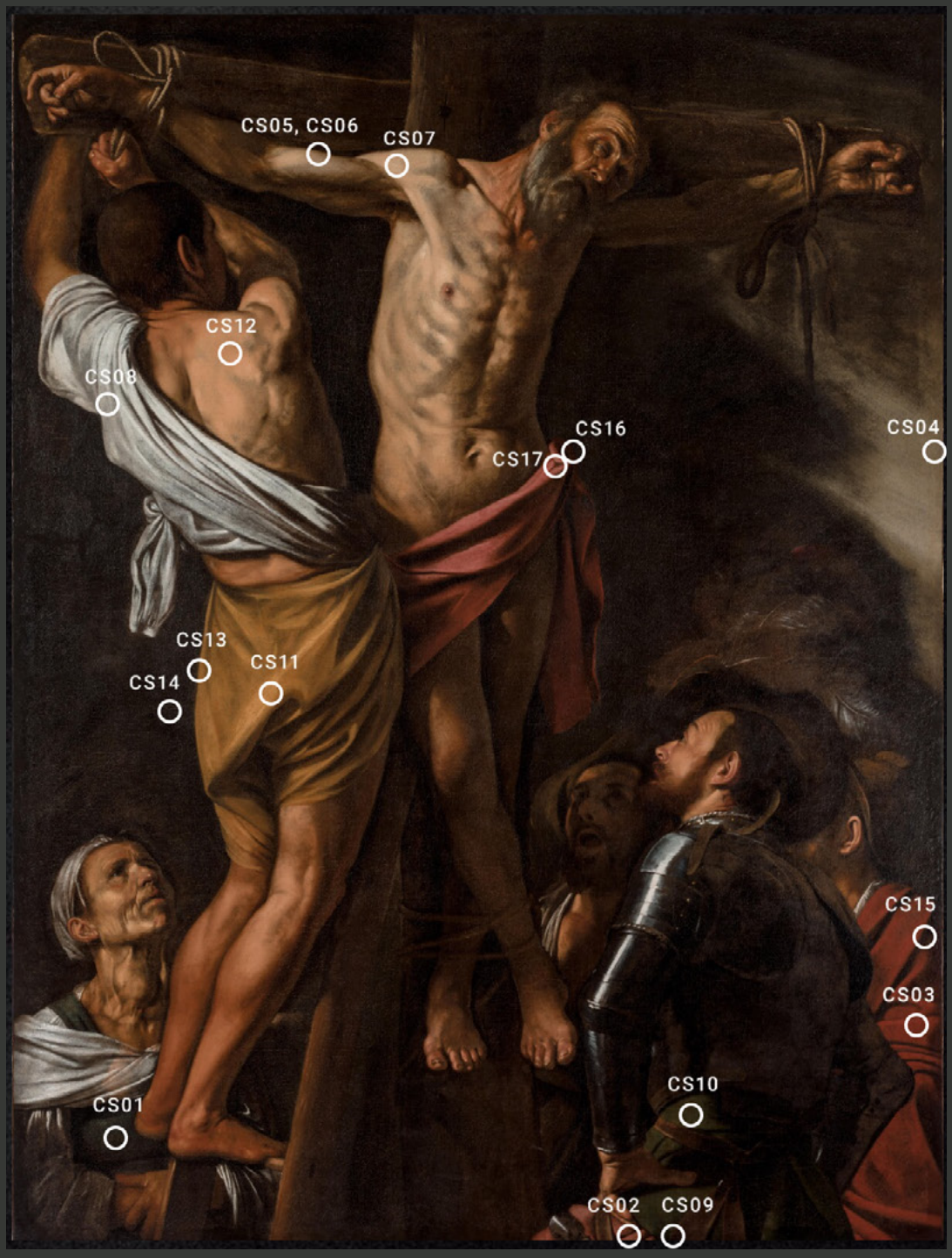


CROSS SECTIONS

GROUND LAYERS

RAMAN SPECTROSCOPY

PAINT LAYERS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

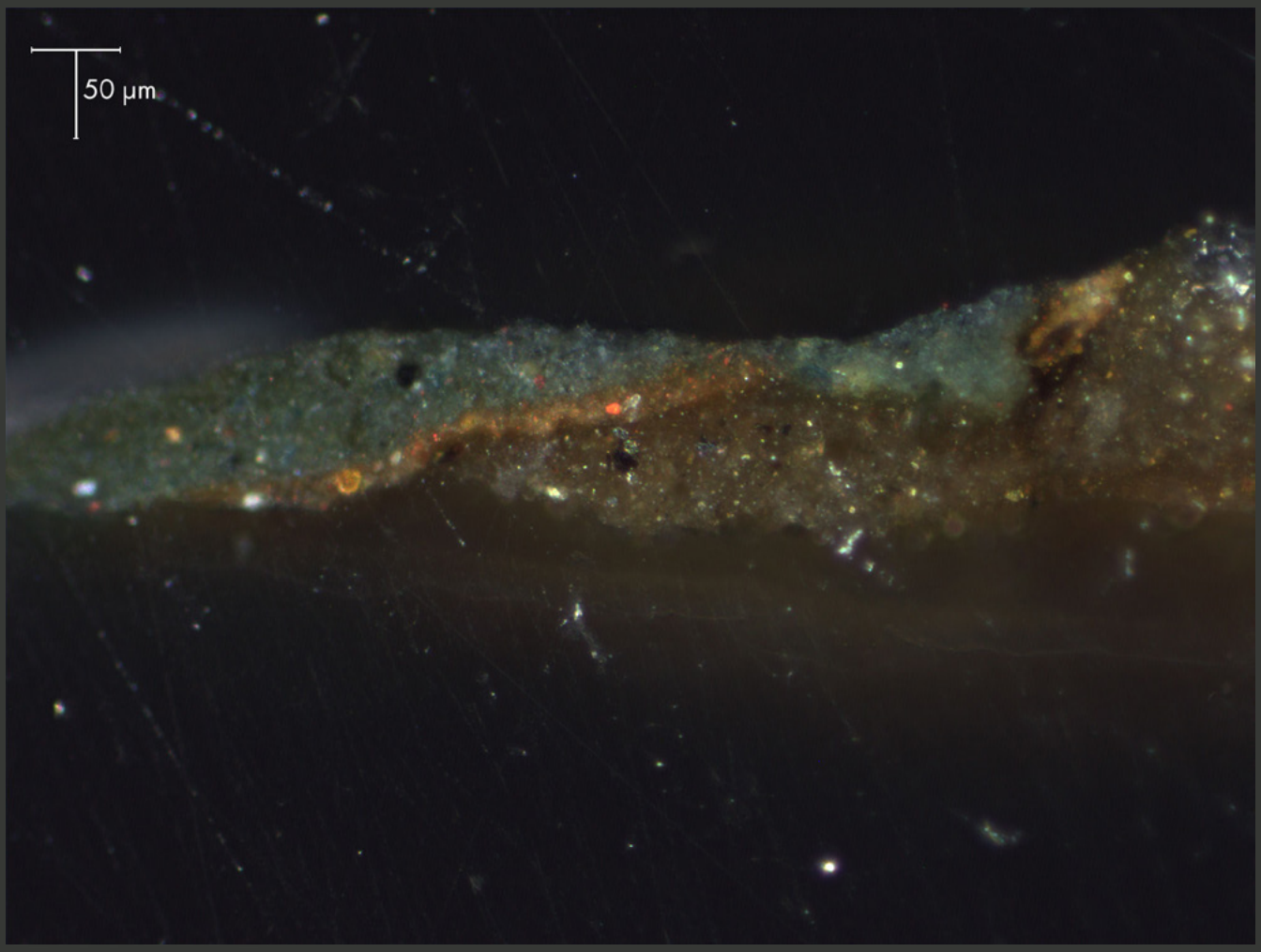
Cross Section 1 (CS01)

Location: Blue-green color in the elderly woman's blouse

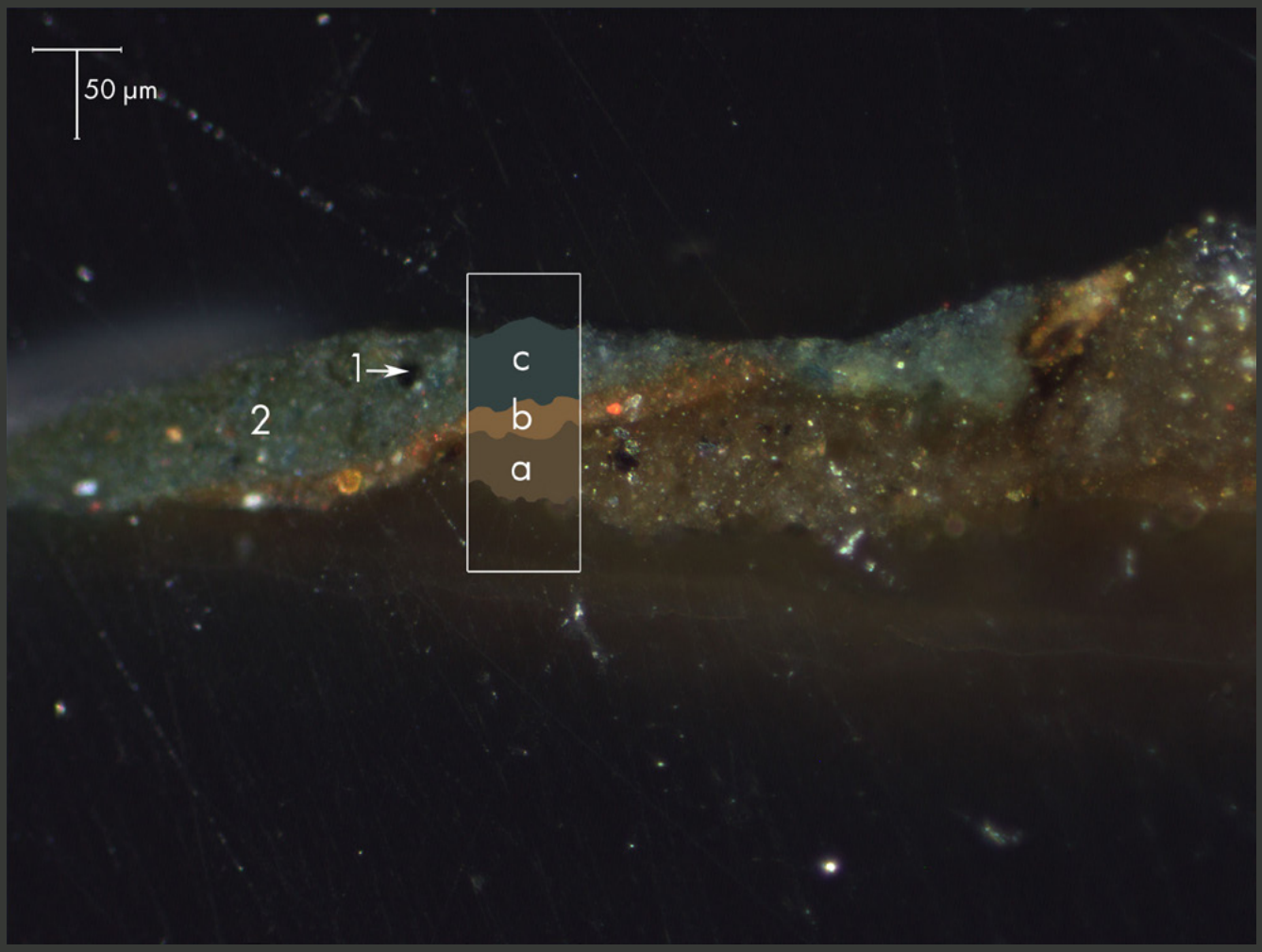
The sample was taken after the treatment was complete to determine the composition of the dark blue-green paint used in the elderly woman's blouse. SEM-EDS analysis was not conducted on this sample; Raman spectroscopy was able to reliably identify the pigments in question.

CROSS SECTIONS

Normal Light Overlay



Layer c: paint layer
Location 1: dark particle verified as carbon black by Raman spectroscopy
Location 2: blue particles verified as azurite by Raman spectroscopy
Layer b: thinly applied yellow-orange paint layer
Layer a: upper ground (oil-bound) layer
Note: The lower ground is missing from this sample.

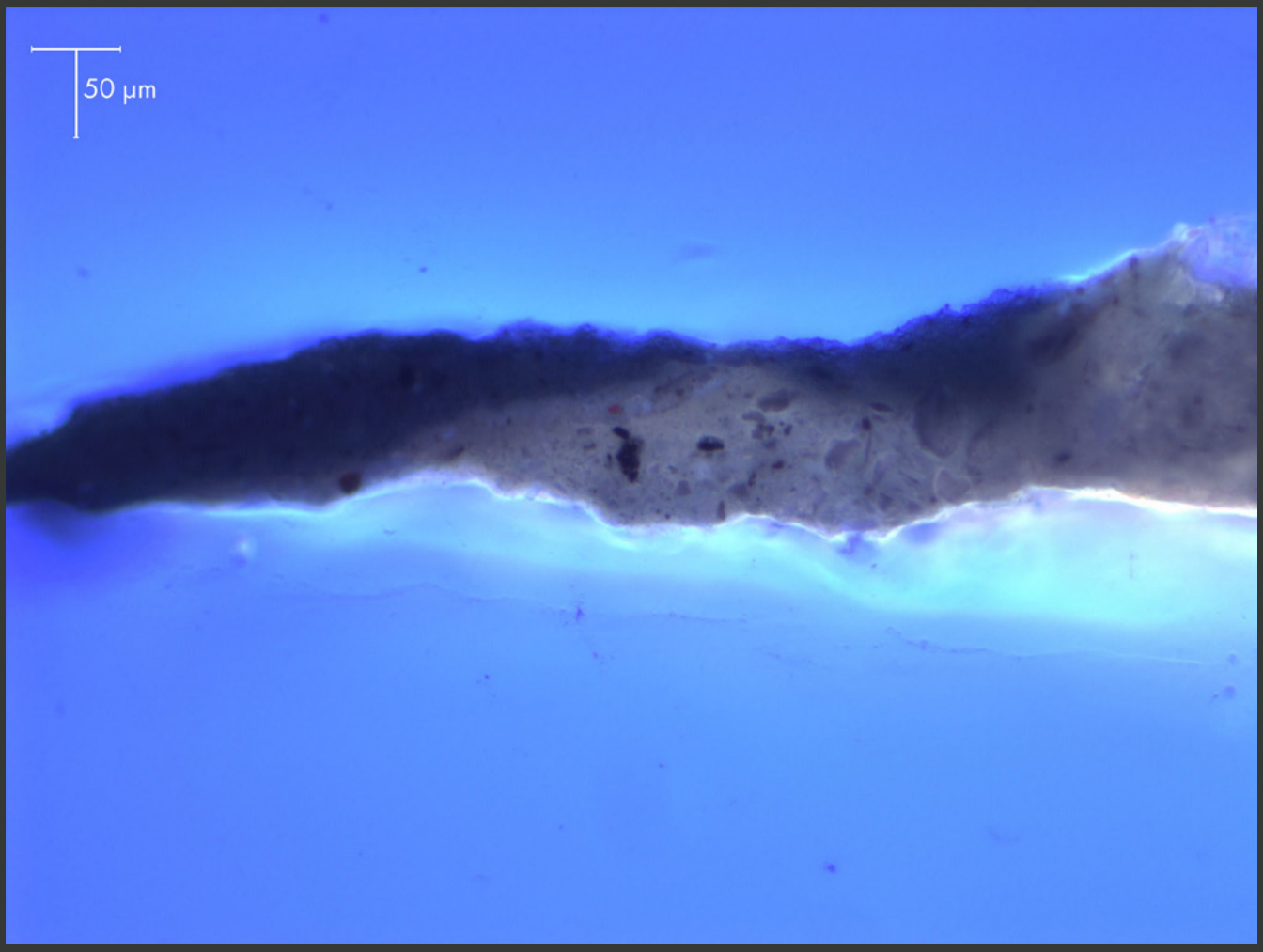


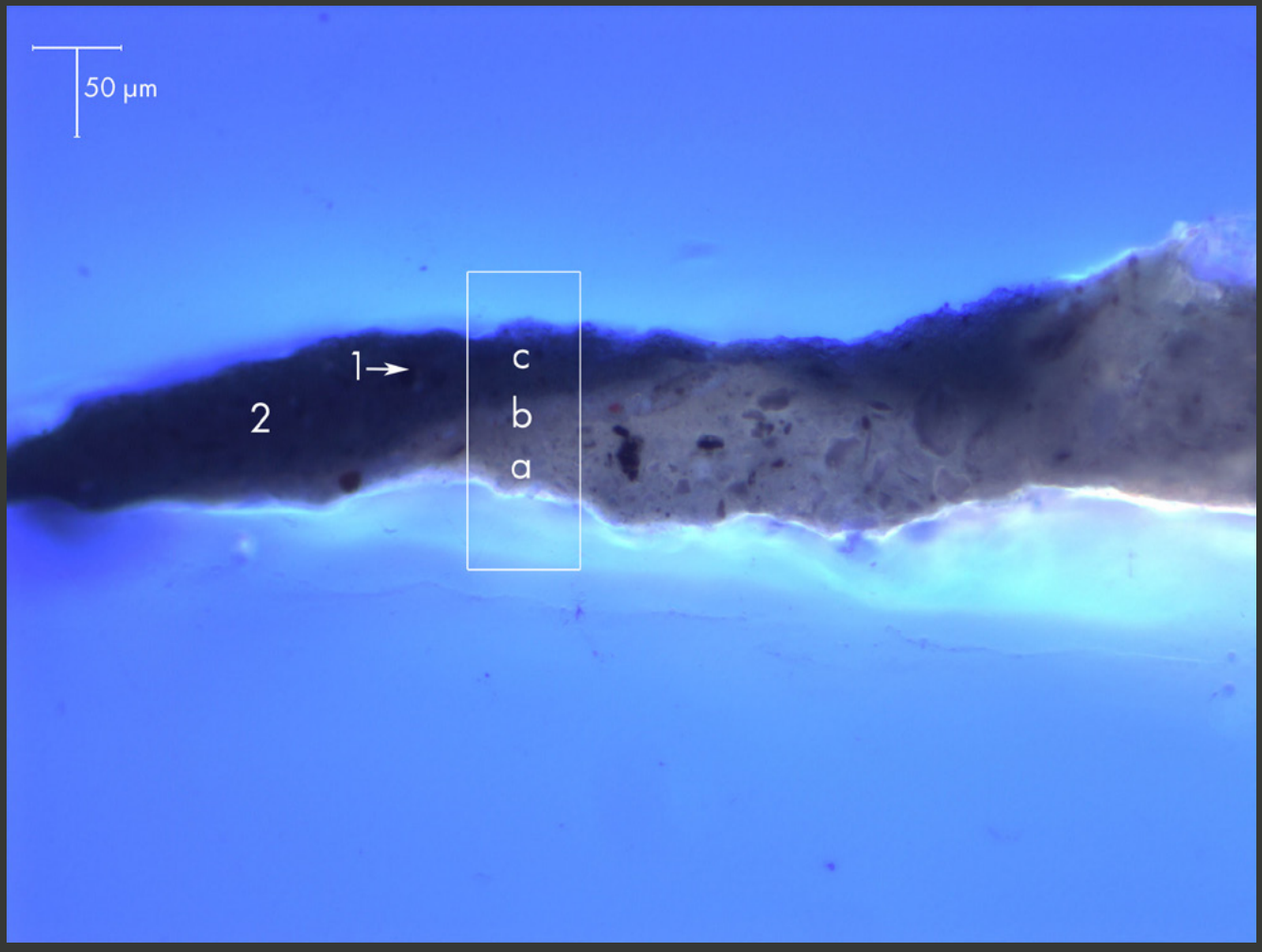
Cross Section 1 (CS01)

Location: Blue-green color in the elderly woman's blouse

Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm)

Overlay



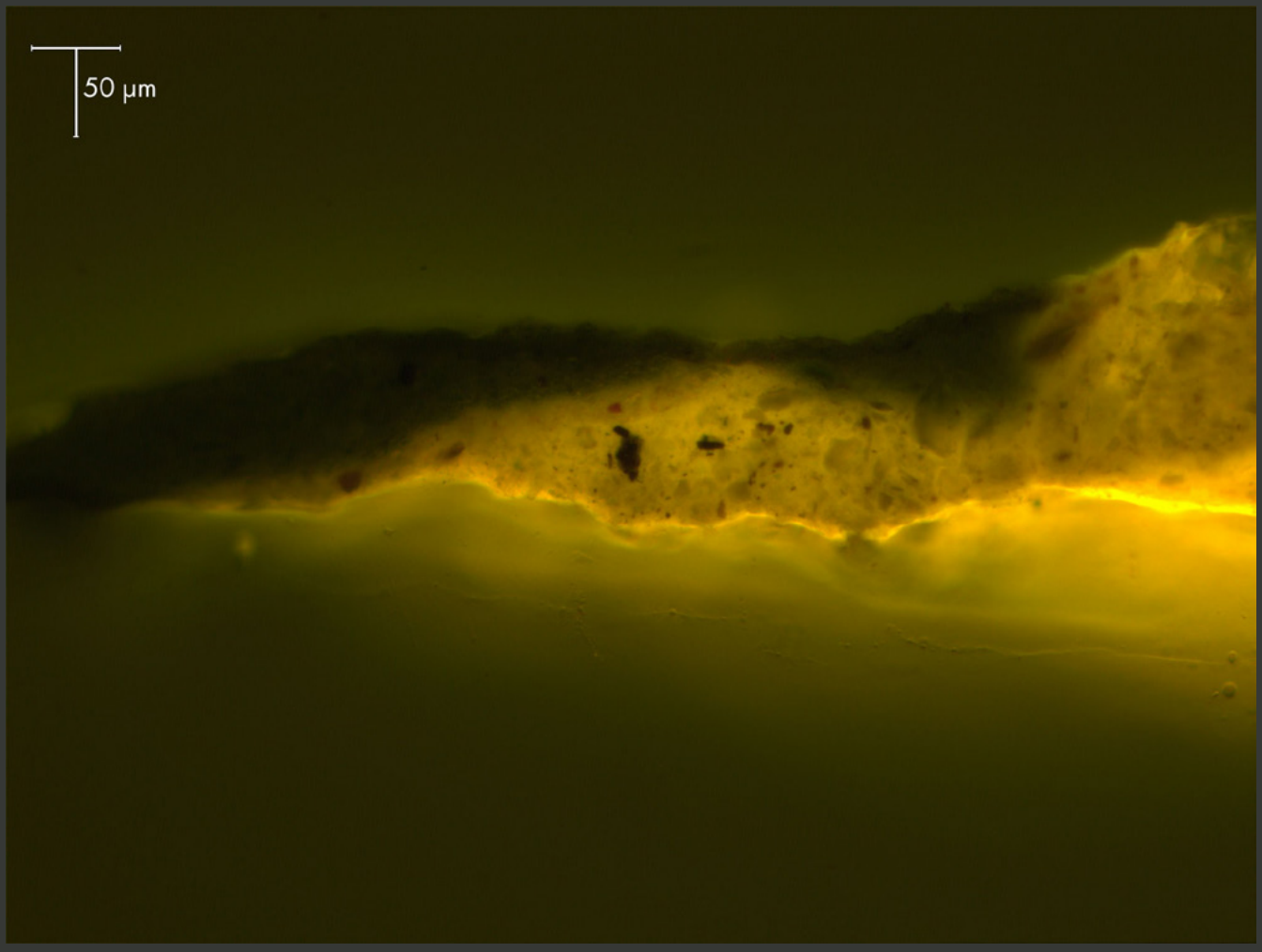

50 µm
1
2
c
b
a

Cross Section 1 (CS01)

Location: Blue-green color in the elderly woman's blouse

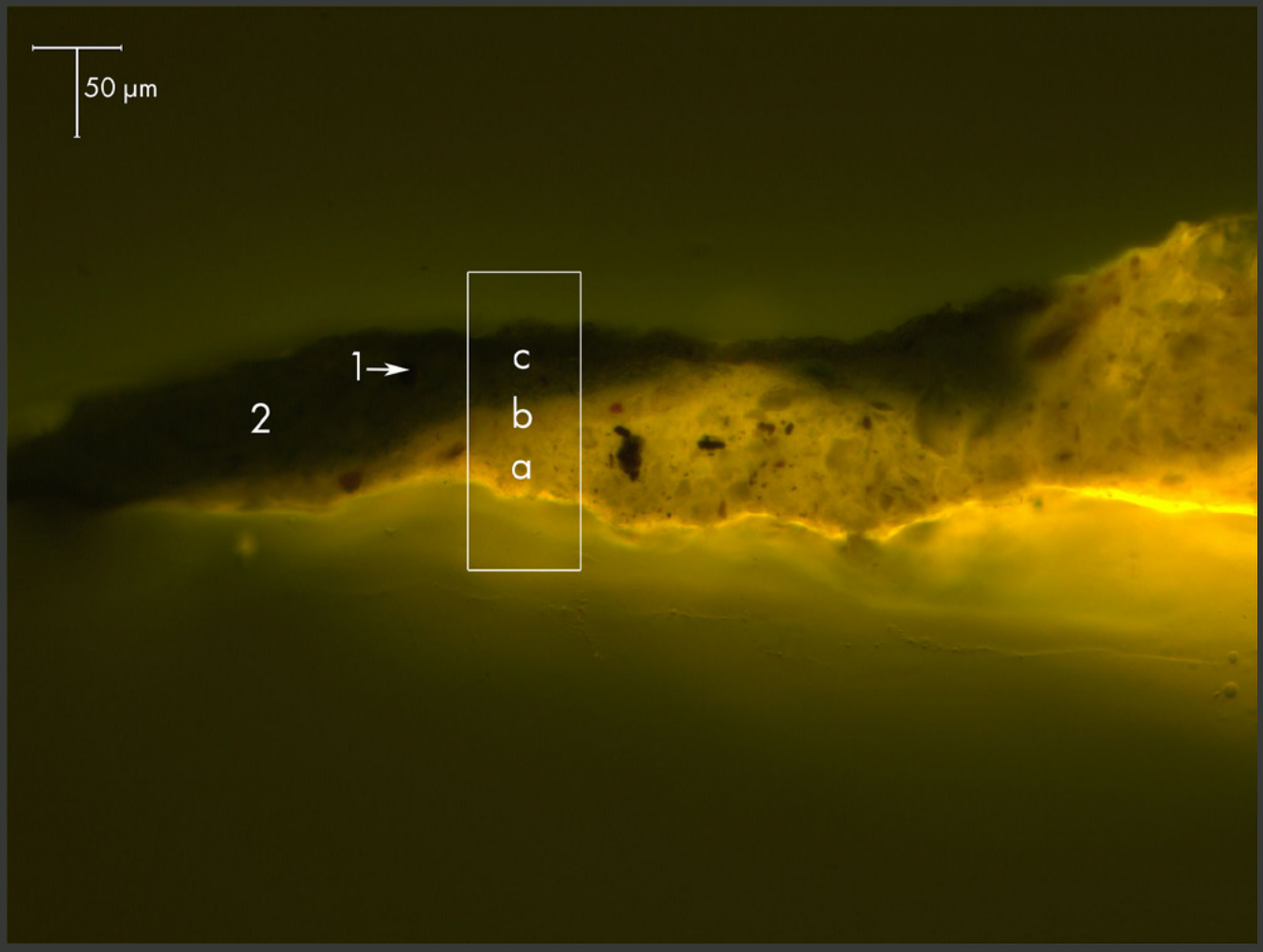
Excitation: blue (450–490 nm)
Emission: green (λ_{em} > 515 nm)

Overlay



GROUND LAYERS

Only the upper ground (layer a) was retained during sample removal; the lower ground remained adhered to the canvas.

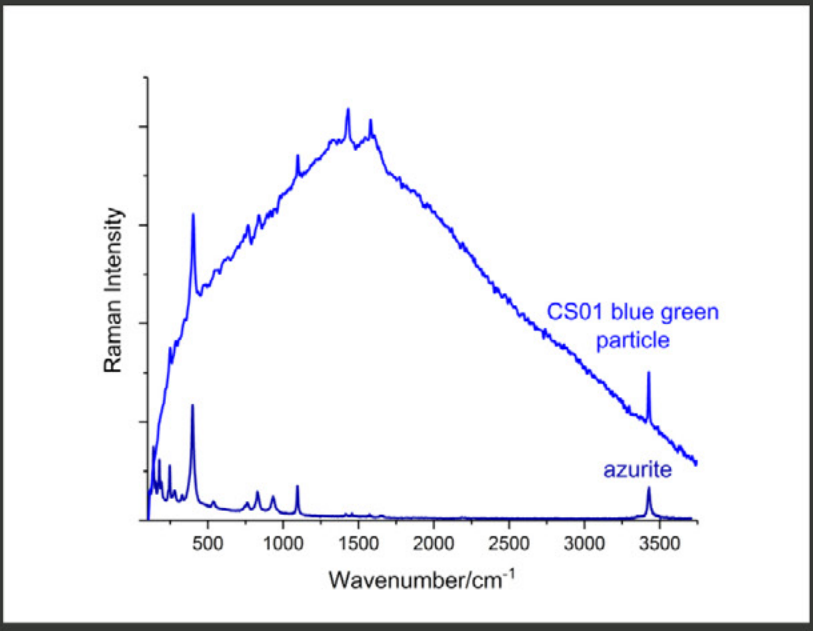

50 µm
1
2
c
b
a

Cross Section 1 (CS01)

Location: Blue-green color in the elderly woman's blouse

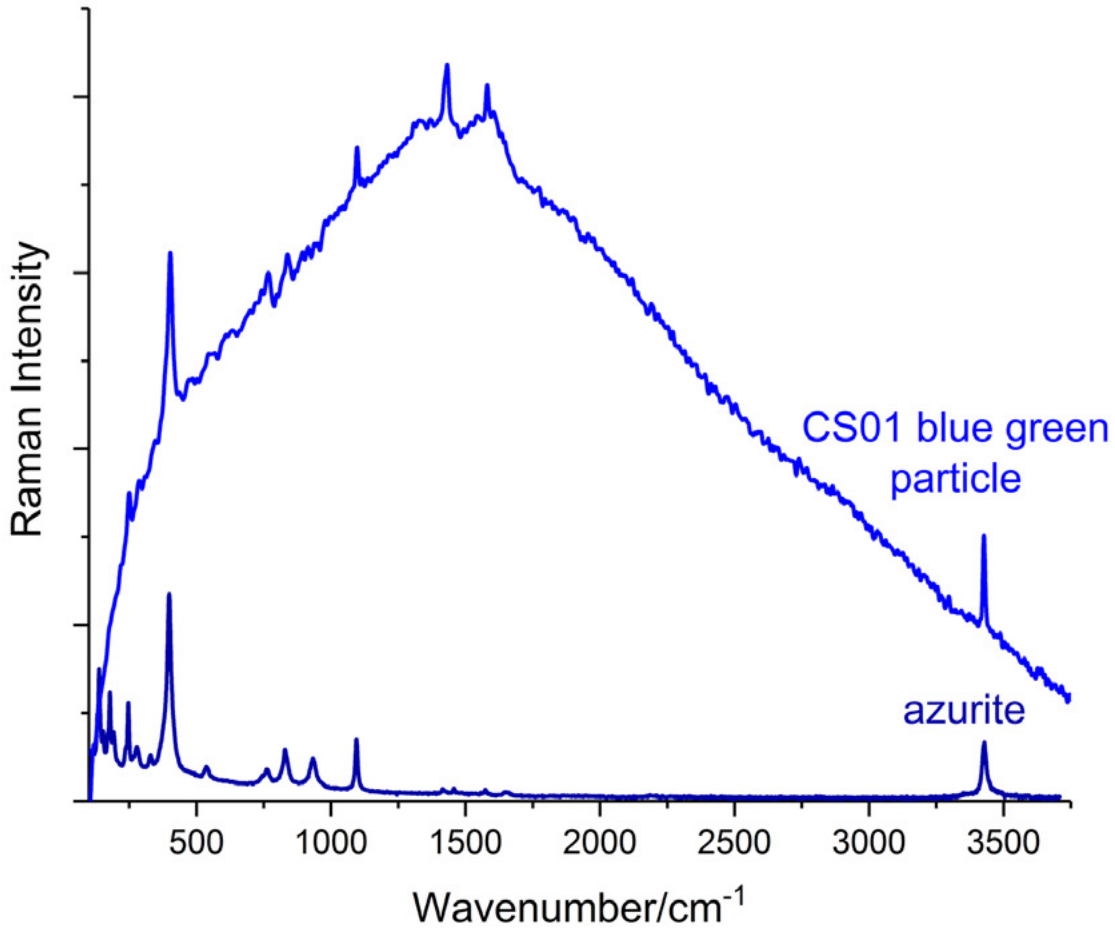
RAMAN SPECTROSCOPY

Raman spectrum for blue-green particle from location 2



PAINT LAYERS

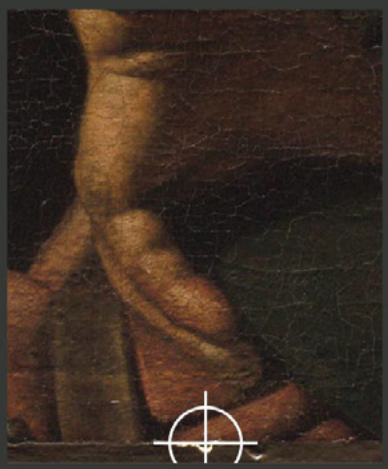
Under normal light the pigment particles appear a dark blue-green color, differing from lighter green malachite particles found in the soldier's waistcoat. Raman spectroscopy confirmed the field of blue pigment particles (c) as azurite ($Cu_3(CO_3)_2(OH)_2$) mixed with carbon (soot) black. A thin, lighter yellow-orange layer (b) is located below the blue-green paint layer. This layer appears to closely match the preparatory layer of the elderly woman's flesh color and may also contribute to the greenish hue of the blouse.

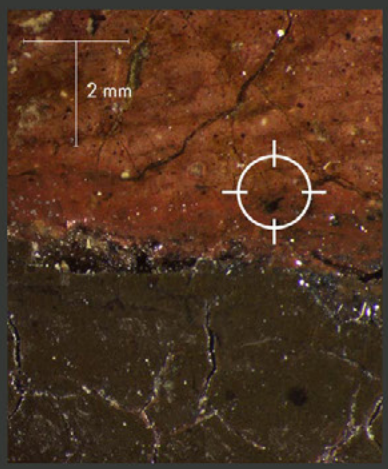

Raman Intensity
CS01 blue green particle
azurite
500
1000
1500
2000
2500
3000
3500
Wavenumber/cm-1

Cross Section 2 (CS02)

Location: Bottom edge of the soldier's salmon-colored trousers

This sample, taken before treatment, was analyzed to study the composition of the ground, paint, and varnish layers in preparation for treatment.





CROSS SECTIONS

GROUND LAYERS

RAMAN SPECTROSCOPY

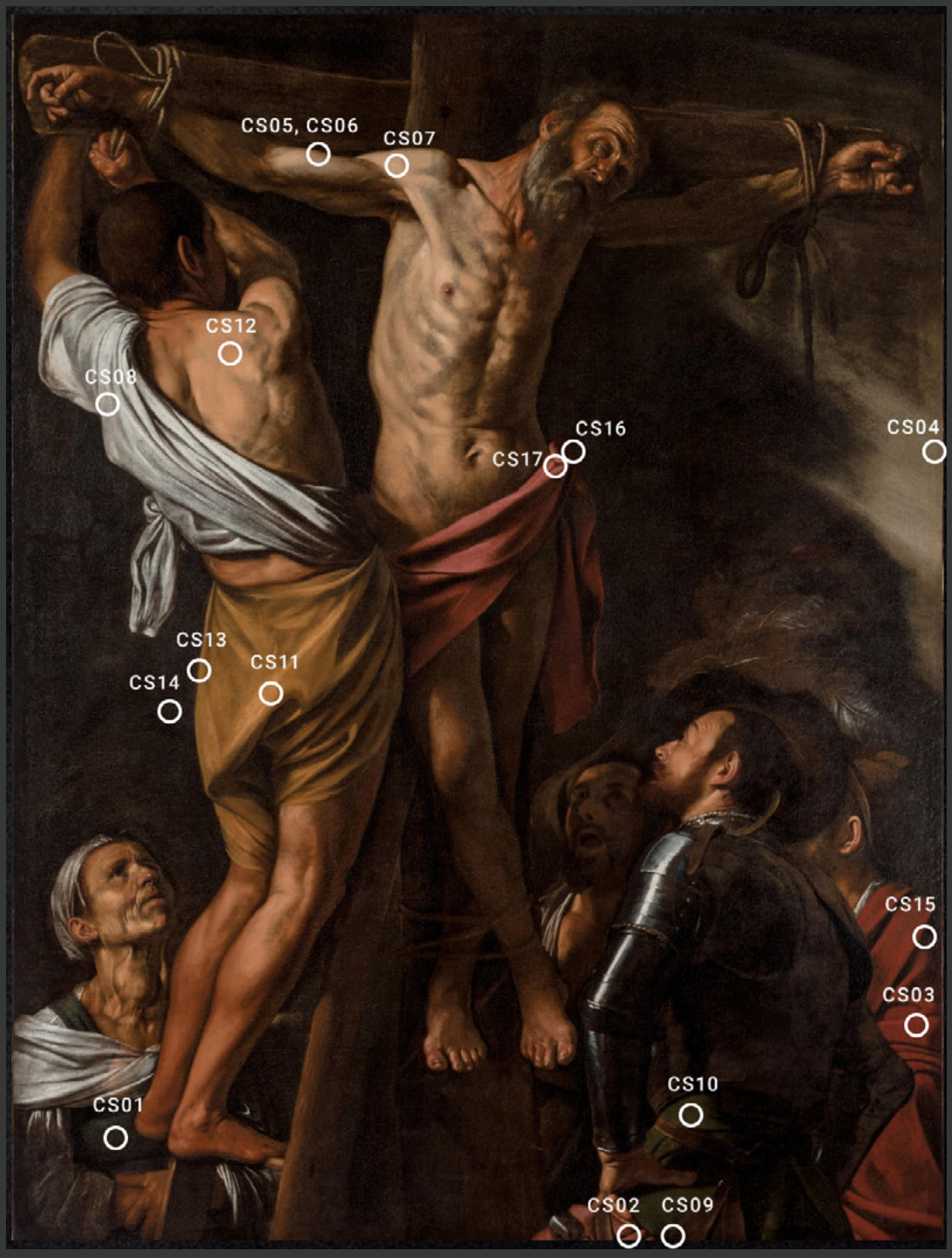
PIGMENTS IDENTIFIED

BSE IMAGES

PAINT LAYERS

SEM-EDS MAPS

SURFACE COATINGS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

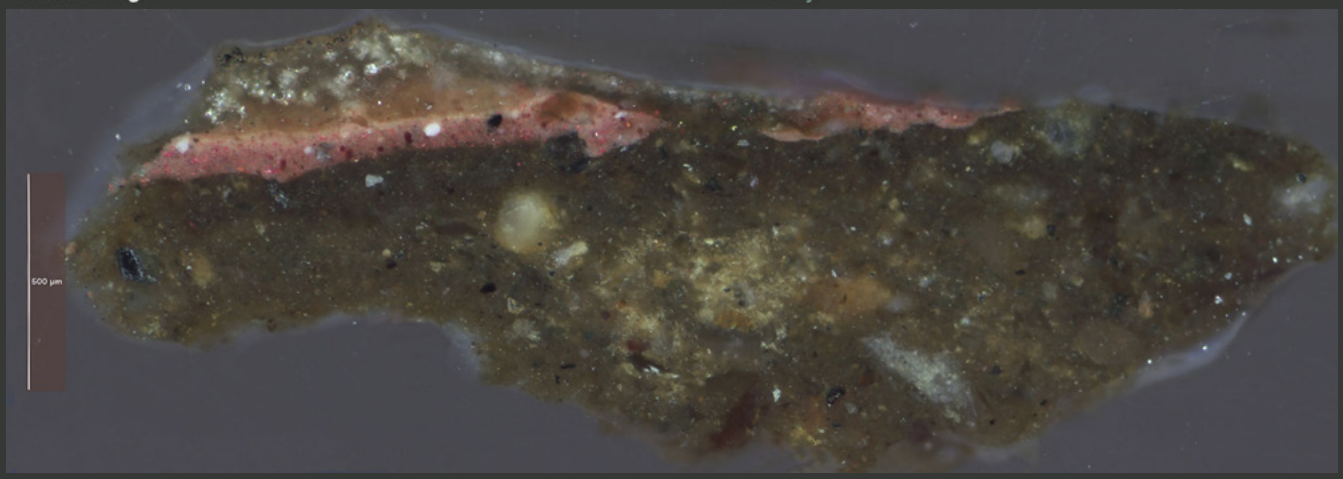
Cross Section 2 (CS02)

Location: Bottom edge of the soldier's salmon-colored trousers

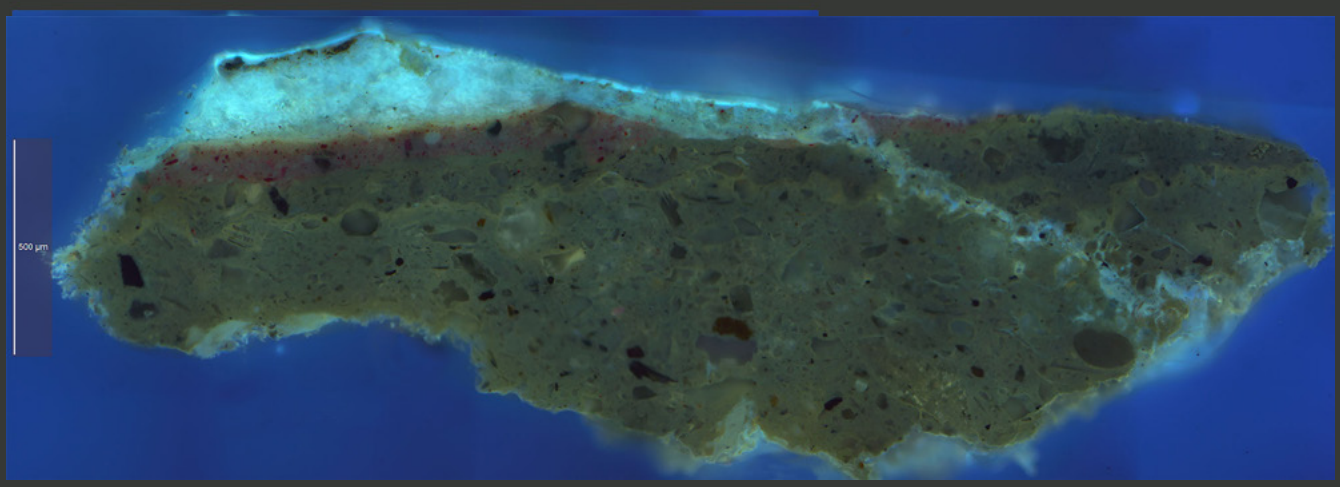
This sample, taken before treatment, was analyzed to study the composition of the ground, paint, and varnish layers in preparation for treatment.

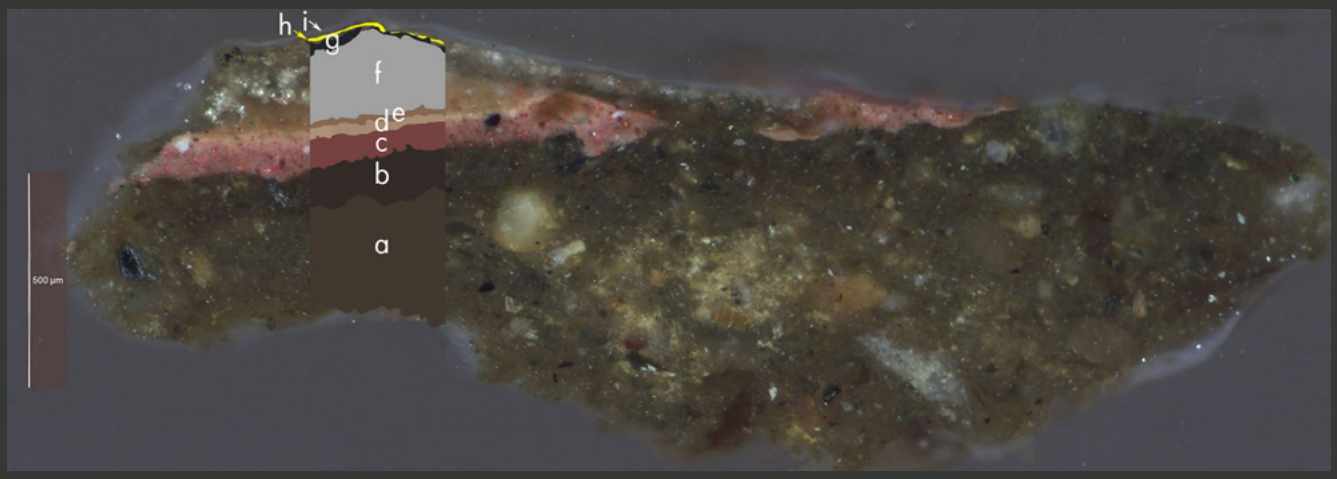
CROSS SECTIONS

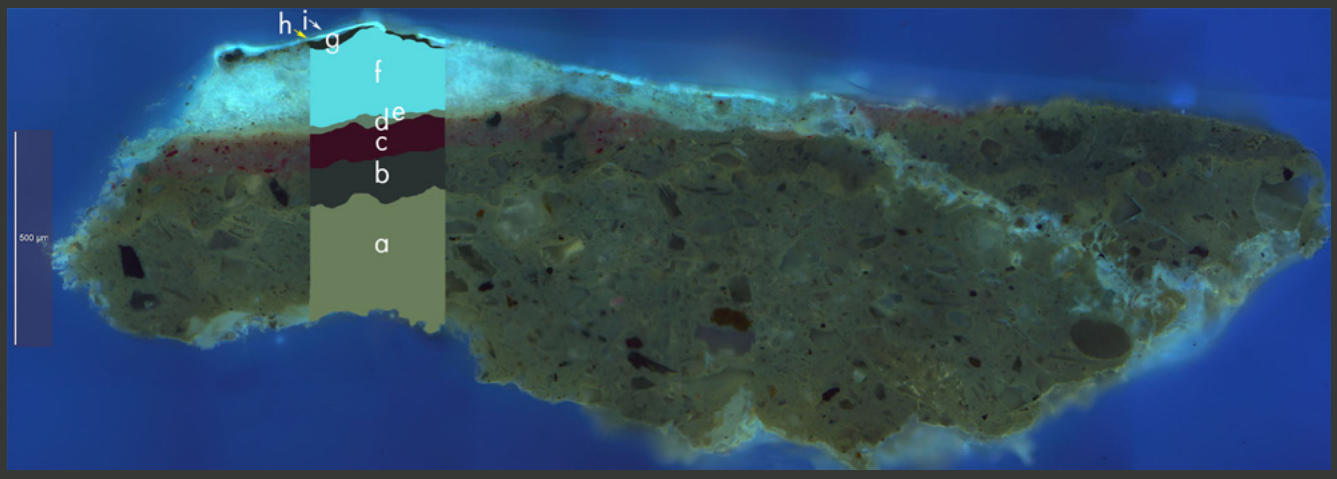
Normal Light Overlay



Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm) Overlay




h
i
g
f
e
d
c
b
a
500 µm


h
i
g
f
e
d
c
b
a
500 µm

Cross Section 2 (CS02)

Location: Bottom edge of the soldier's salmon-colored trousers

GROUND LAYERS

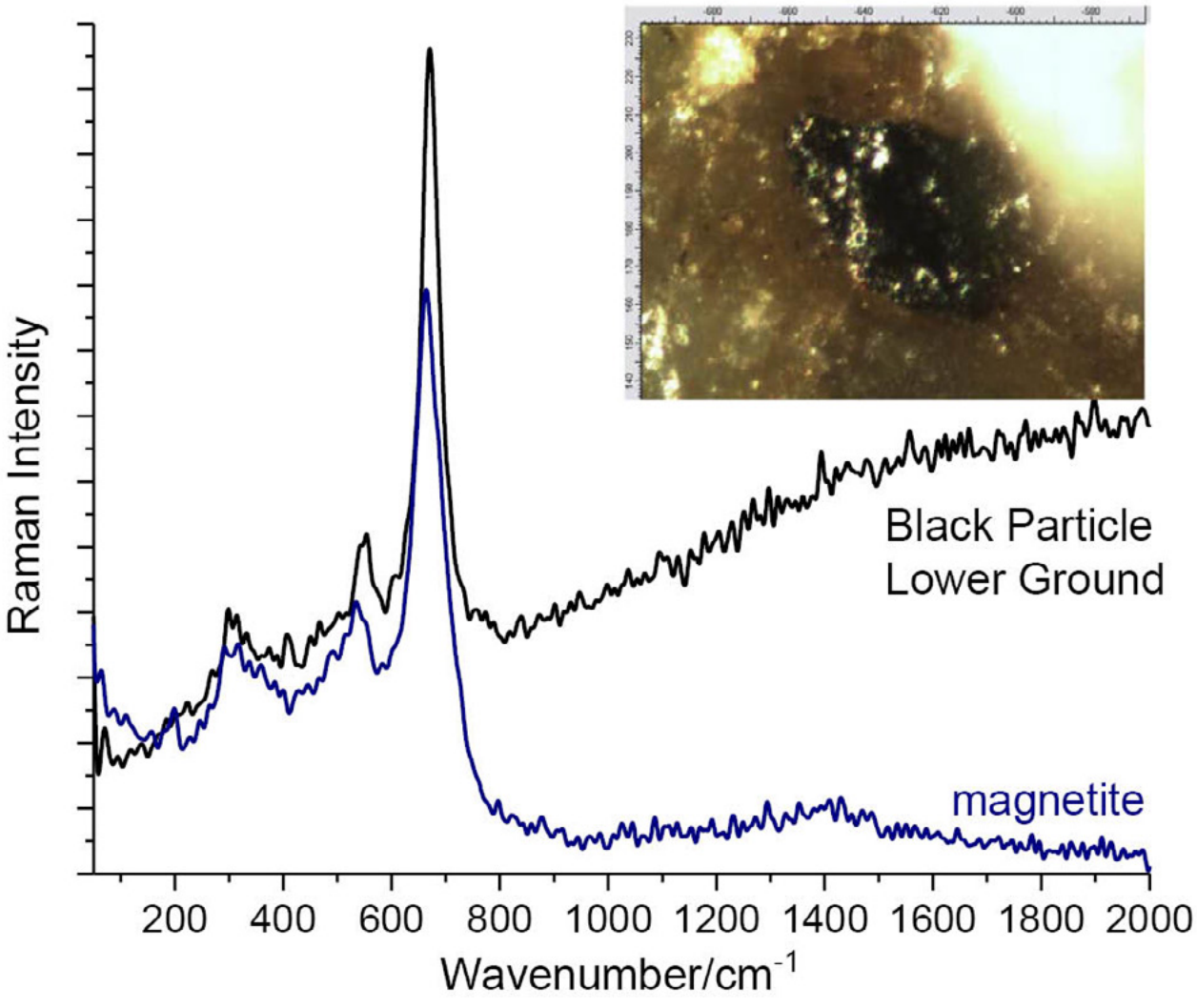
The sample was first encapsulated in an emulsion polymer (diluted Rhoplex™ M-200) to protect the most recent varnish layer, applied in 1974, from dissolving in the embedding medium (Bio-plastic®).

Two distinct ground layers (a, b) are present, visible under normal illumination and UV sources. The upper ground layer is slightly darker when viewed under normal and UV radiation, although the particle distribution and morphology are mostly similar.

Based on elemental mapping by SEM-EDS of the lower ground layer, there is an even distribution of aluminosilicate-based (Al, Si) particles; an even and wide distribution of particles containing iron, titanium, and magnesium (Fe, Ti, Mg); a small amount of copper (Cu), some of which corresponds to blue particles identified as azurite by Raman spectroscopy; and larger particles of chalk ($CaCO_3$). A few large, black irregularly shaped iron-rich particles are present in the lower ground at the far left of the sample, identified by Raman spectroscopy as magnetite (Fe_3O_4).

RAMAN SPECTROSCOPY

Other iron-containing particles have a shiny metallic appearance and framboid structure under high magnification and were found by Raman spectroscopy to be pyrite (iron sulfide, FeS_2). A few larger black particles of soot black also were identified. Lead white (lead carbonate, $2PbCO_3\,Pb(OH)_2$) is mostly absent from the ground layers.

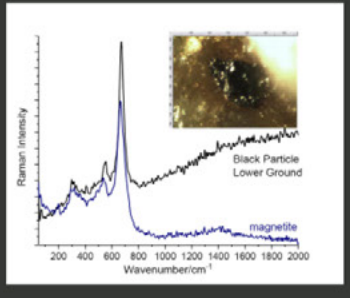

Raman Intensity
Black Particle
Lower Ground
magnetite
200
400
600
800
1000
1200
1400
1600
1800
2000
Wavenumber/cm-1

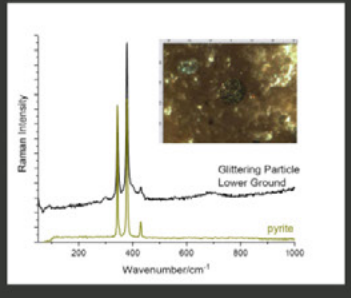
Cross Section 2 (CS02)

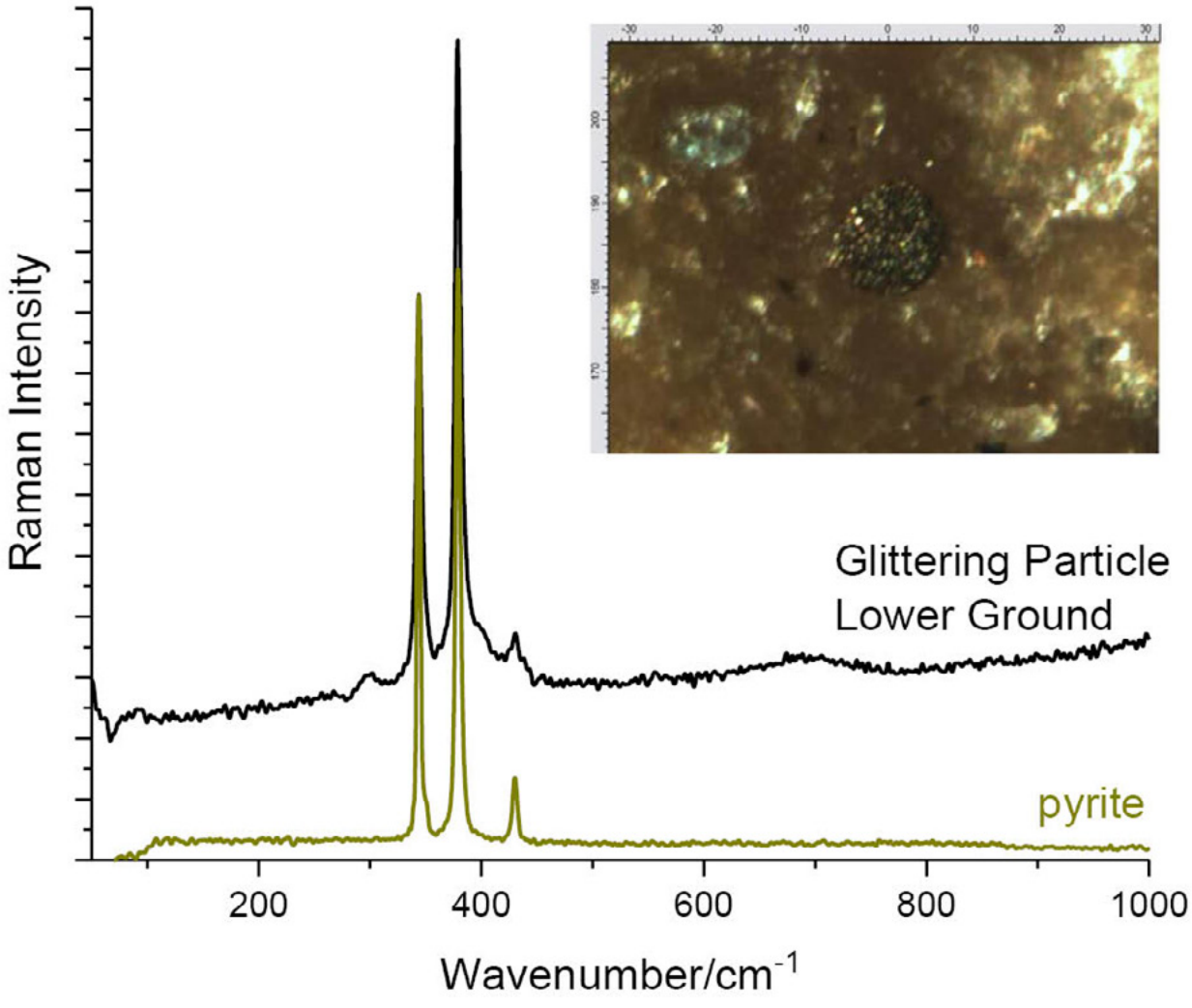
Location: Bottom edge of the soldier's salmon-colored trousers

RAMAN SPECTROSCOPY

Other iron-containing particles have a shiny metallic appearance and framboid structure under high magnification and were found by Raman spectroscopy to be pyrite (iron sulfide, FeS_2). A few larger black particles of soot black also were identified. Lead white (lead carbonate, $2PbCO_3\ Pb(OH)_2$) is mostly absent from the ground layers.






Raman Intensity
Glittering Particle
Lower Ground
pyrite
200
400
600
800
1000
Wavenumber/cm-1

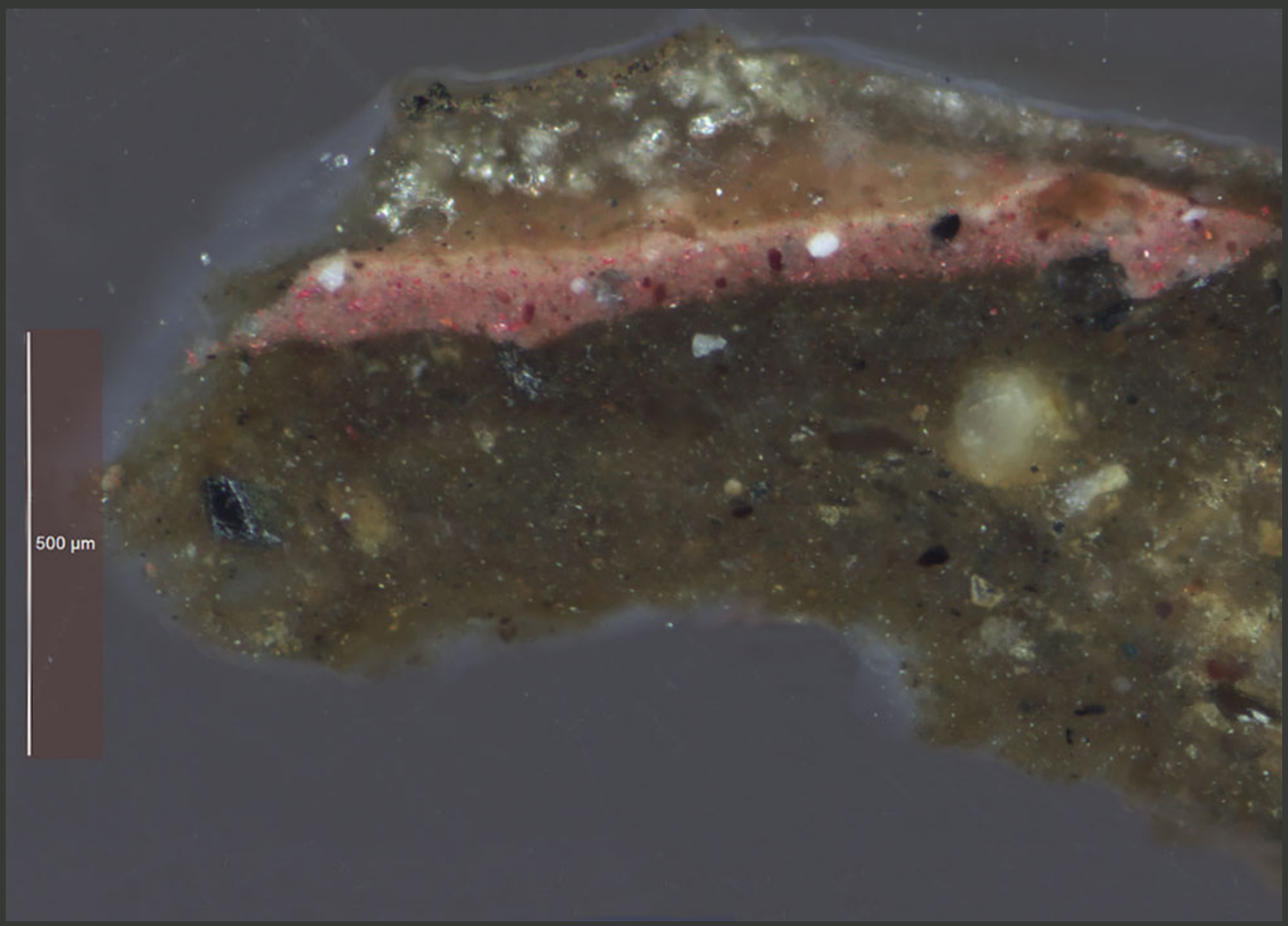
Cross Section 2 (CS02)

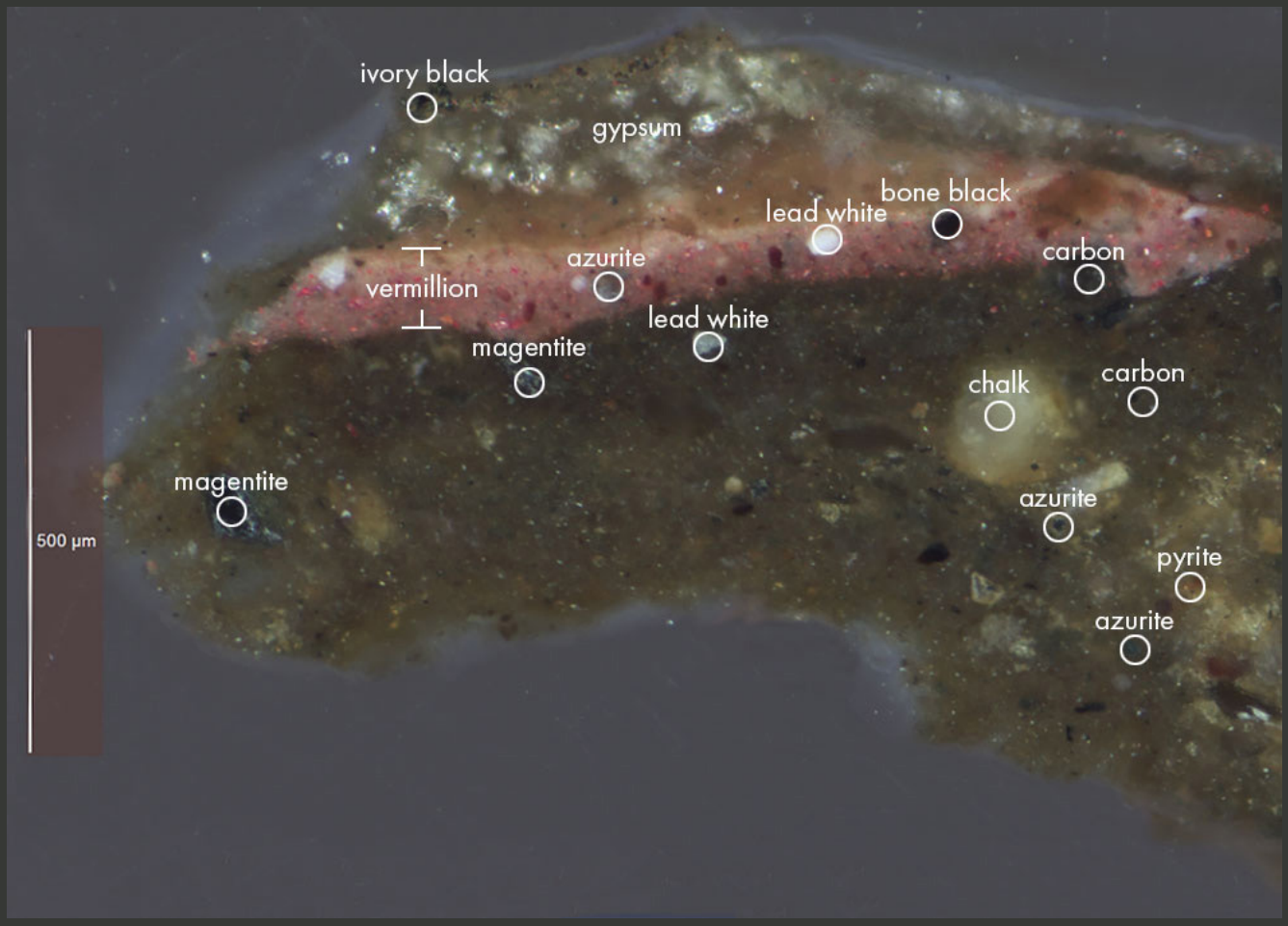
Location: Bottom edge of the soldier's salmon-colored trousers

PIGMENTS IDENTIFIED BY RAMAN SPECTROSCOPY

Normal Light

Overlay

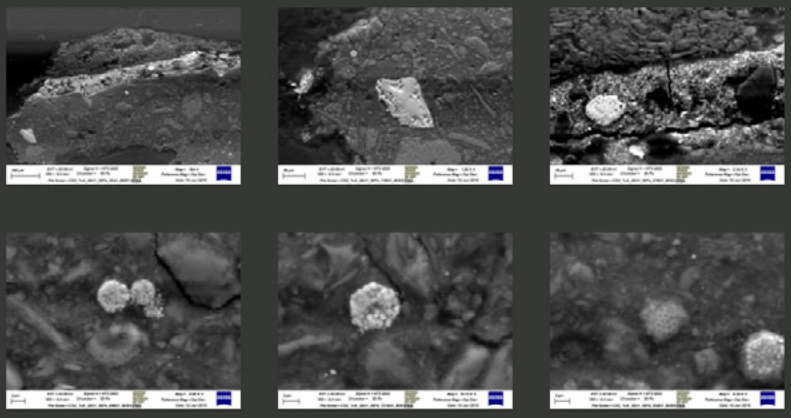



ivory black
gypsum
lead white
bone black
carbon
azurite
vermillion
lead white
magentite
chalk
carbon
magentite
azurite
pyrite
azurite
500 µm

Cross Section 2 (CS02)

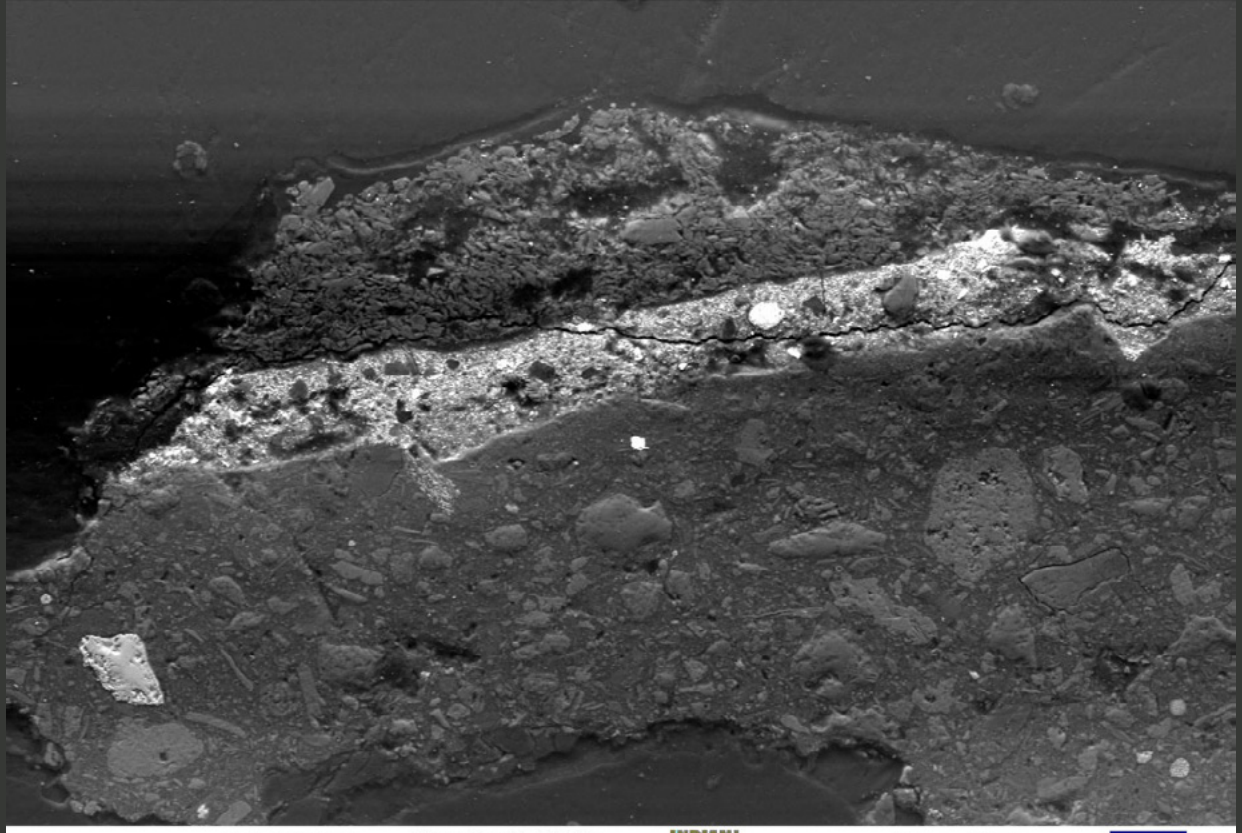
Location: Bottom edge of the soldier's salmon-colored trousers

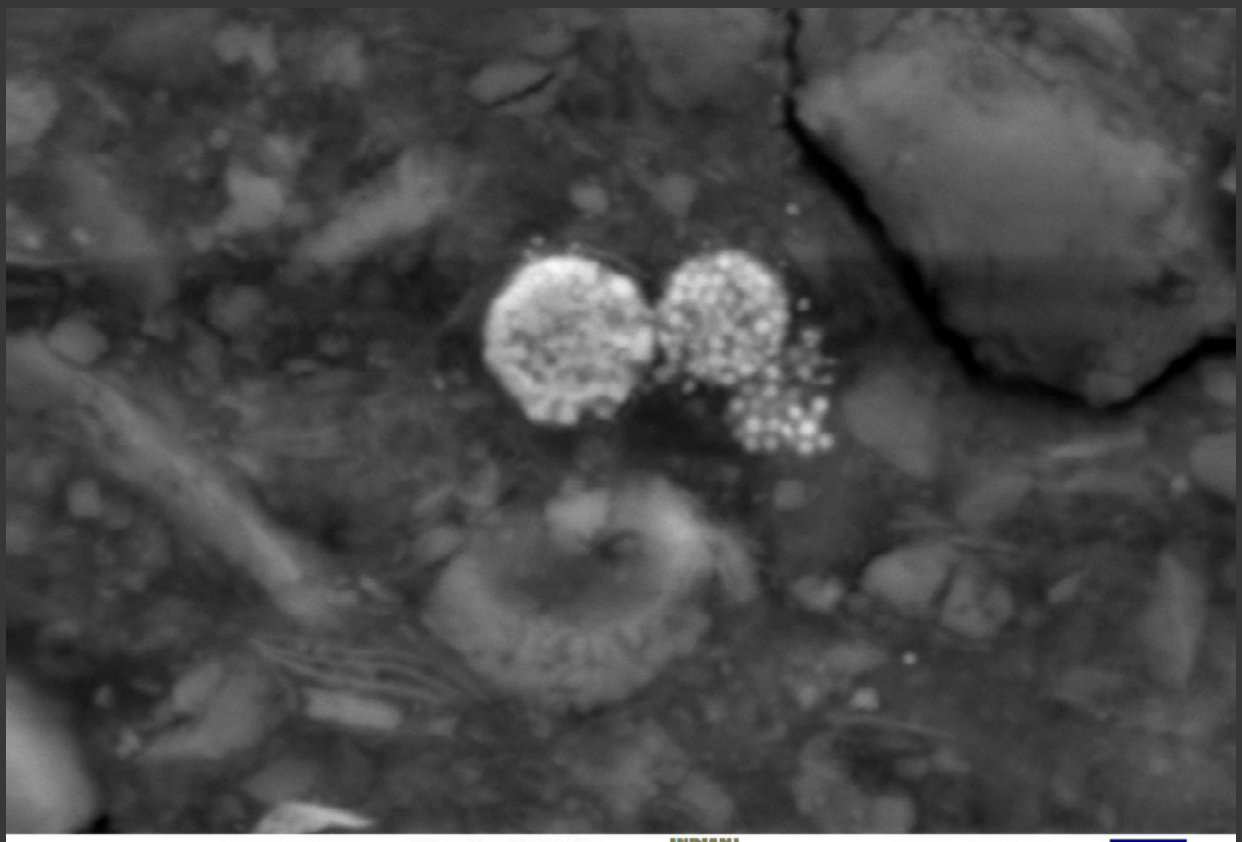
BSE IMAGES

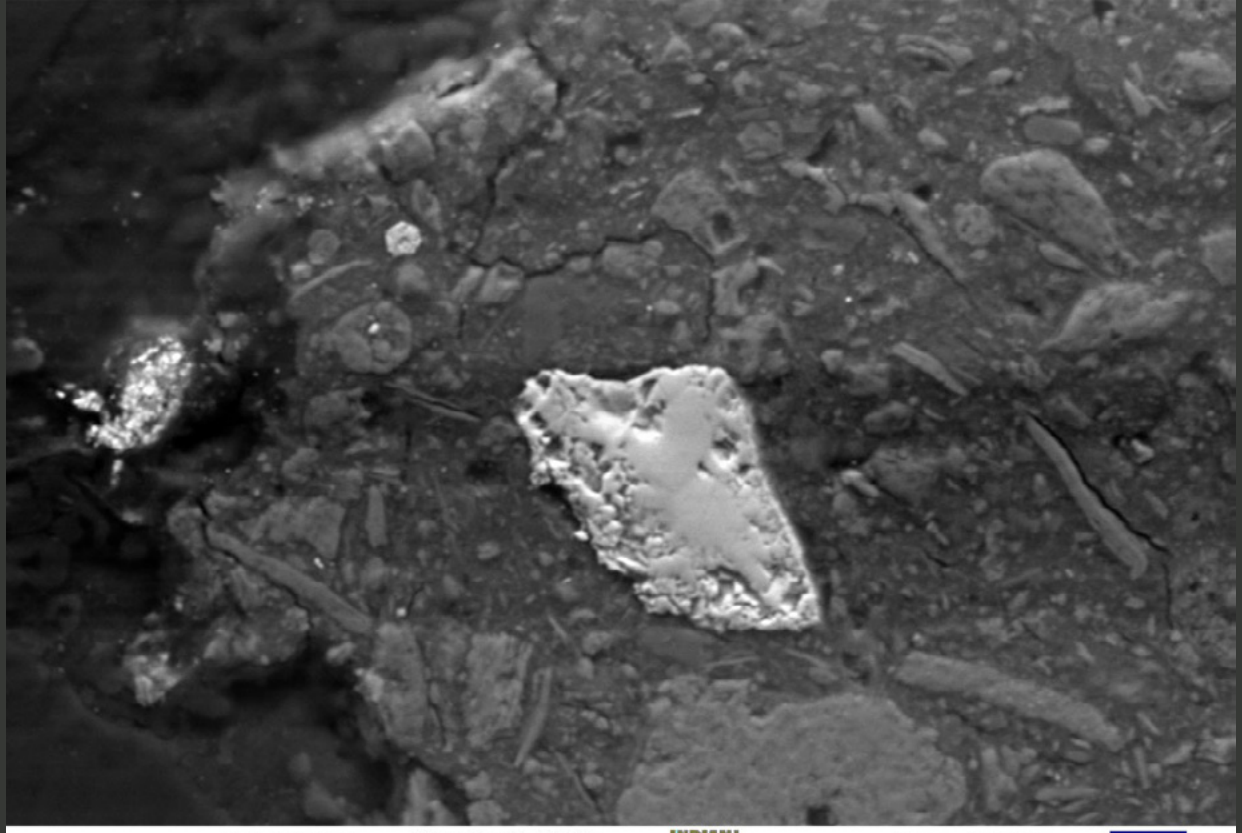


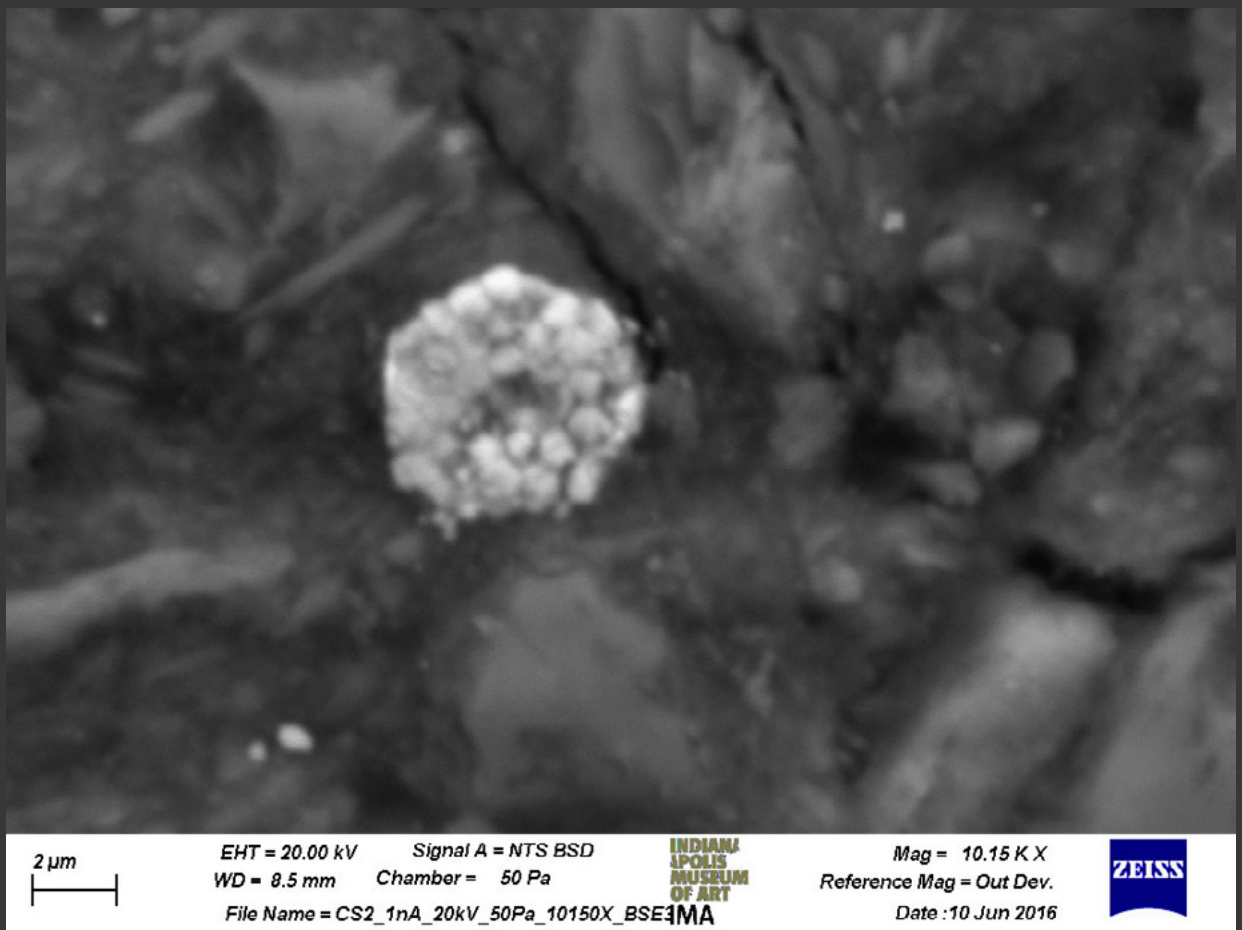
Backscatter electron (BSE) images: top left, overall view of the left portion; top middle, large magnetite particle in the lower ground layer; top right, lead white particle in the paint layer; bottom left, pyrite framboids with microfossil in the lower ground; bottom middle, ring-shaped formation of pyrite in the lower ground; bottom right, two pyrite framboids in the lower ground.

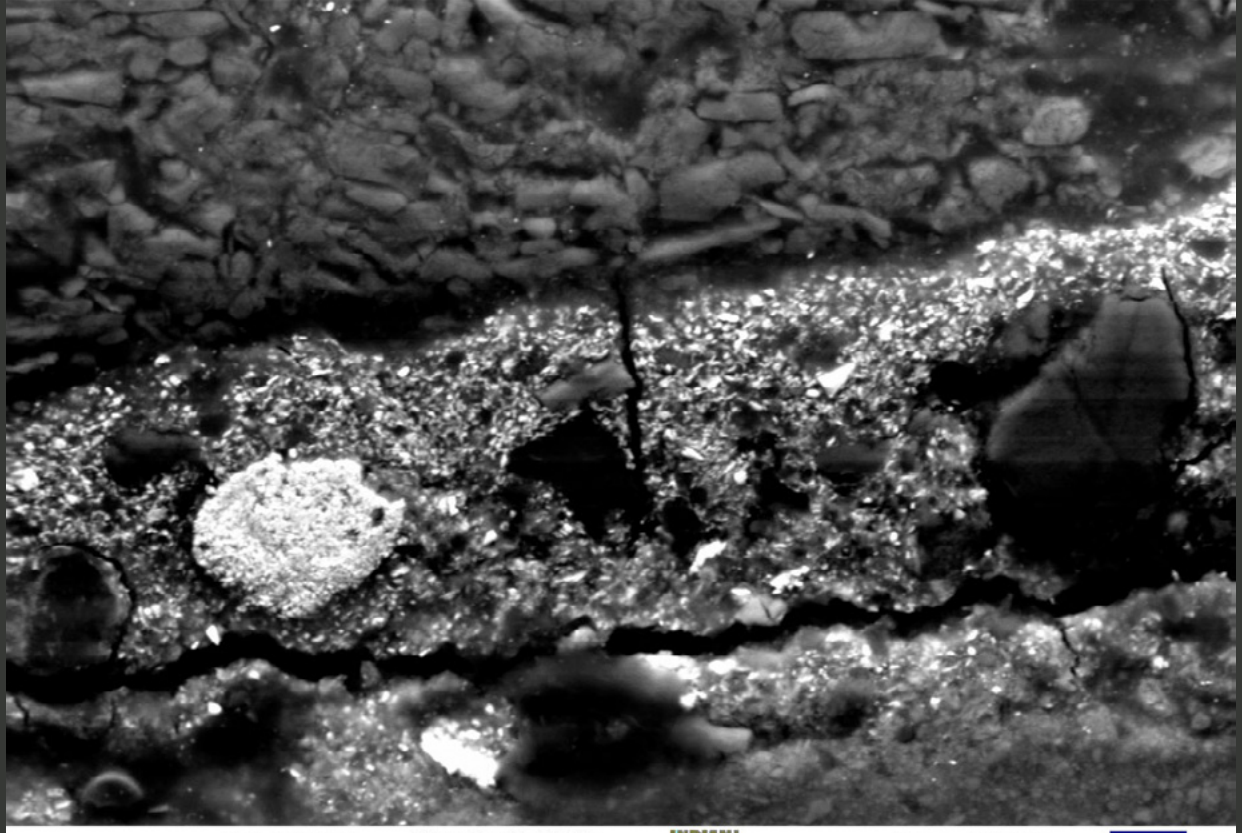
Fragments of microfossils and pyrite spheroids (framboids) are found in the lower ground structure. Similar fragments have been documented in the ground layers of Caravaggio's *Saint Francis in Meditation* (Galleria Nazionale d'Arte Antica, Rome). Pyrite particles were also found in the ground layer of his *Madonna Palafrenieri* (Villa Borghese, Rome).

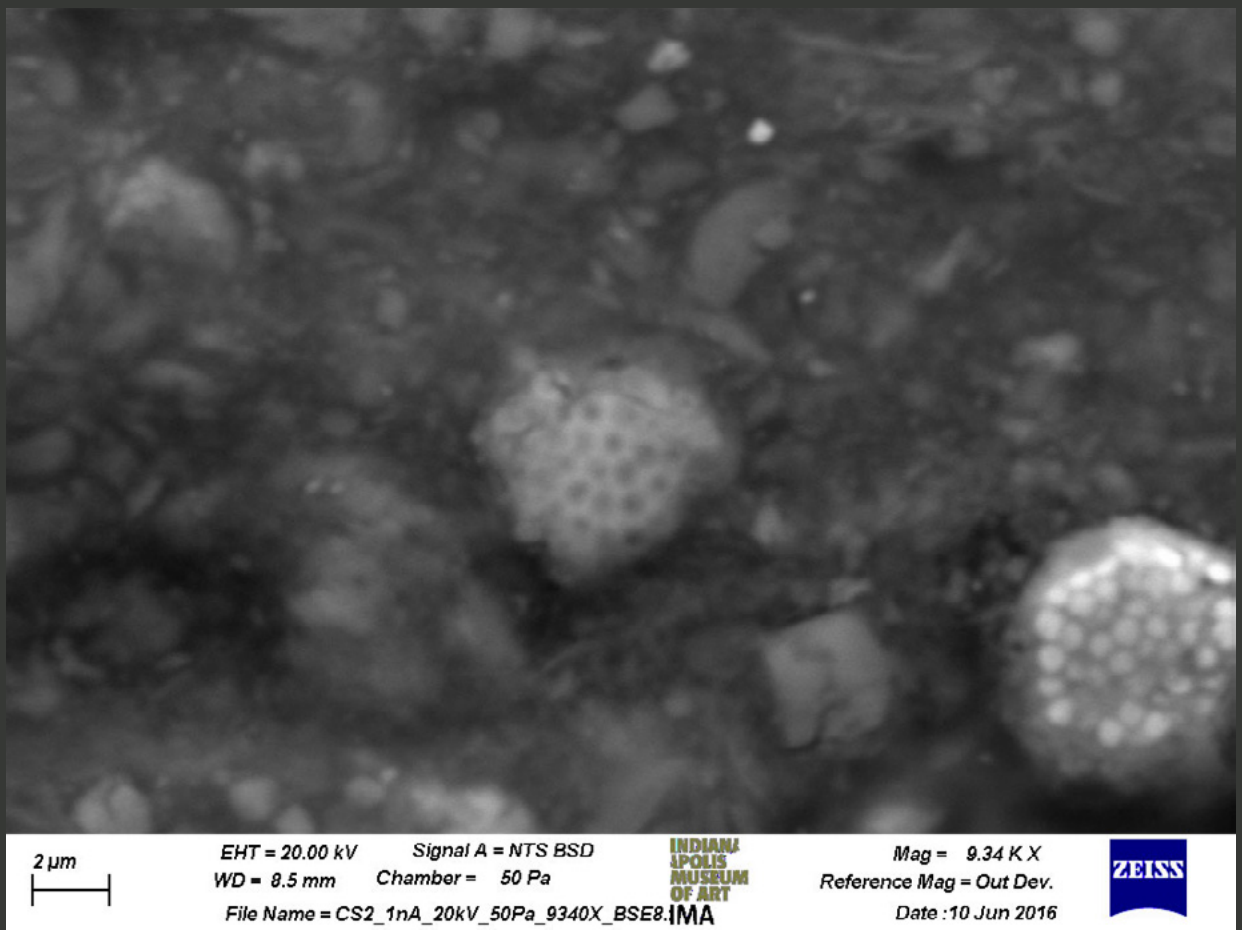

100 µm
EHT = 20.00 kV
WD = 8.5 mm
Signal A = NTS BSD
Chamber = 50 Pa
File Name = CS2_1nA_20kV_50Pa_364X_BSE1.tif
INDIANAPOLIS MUSEUM OF ART
IMA
Mag = 364 X
Reference Mag = Out Dev.
Date :10 Jun 2016
ZEISS


2 µm
EHT = 20.00 kV
WD = 8.5 mm
Signal A = NTS BSD
Chamber = 50 Pa
File Name = CS2_1nA_20kV_50Pa_8960X_BSE5.
INDIANAPOLIS MUSEUM OF ART
IMA
Mag = 8.96 K X
Reference Mag = Out Dev.
Date :10 Jun 2016
ZEISS


20 µm
EHT = 20.00 kV
WD = 8.5 mm
Signal A = NTS BSD
Chamber = 50 Pa
File Name = CS2_1nA_20kV_50Pa_1380X_BSE2.tif
INDIANAPOLIS MUSEUM OF ART
IMA
Mag = 1.38 K X
Reference Mag = Out Dev.
Date :10 Jun 2016
ZEISS


2 µm
EHT = 20.00 kV
WD = 8.5 mm
Signal A = NTS BSD
Chamber = 50 Pa
File Name = CS2_1nA_20kV_50Pa_10150X_BSE1.tif
INDIANAPOLIS MUSEUM OF ART
IMA
Mag = 10.15 K X
Reference Mag = Out Dev.
Date :10 Jun 2016
ZEISS


10 µm
EHT = 20.00 kV
WD = 8.5 mm
Signal A = NTS BSD
Chamber = 50 Pa
File Name = CS2_1nA_20kV_50Pa_2180X_BSE4.tif
INDIANAPOLIS MUSEUM OF ART
IMA
Mag = 2.18 K X
Reference Mag = Out Dev.
Date :10 Jun 2016
ZEISS


2 µm
EHT = 20.00 kV
WD = 8.5 mm
Signal A = NTS BSD
Chamber = 50 Pa
File Name = CS2_1nA_20kV_50Pa_9340X_BSE8.tif
INDIANAPOLIS MUSEUM OF ART
IMA
Mag = 9.34 K X
Reference Mag = Out Dev.
Date :10 Jun 2016
ZEISS

Cross Section 2 (CS02)

Location: Bottom edge of the soldier's salmon-colored trousers

PAINT LAYERS

The lower portion of the paint layer (c) is composed of fine light red particles consistent with vermilion (HgS). These are interspersed with lead white and darker, more translucent particles consistent with a red lake (organic dye). The lead white was verified by Raman spectroscopy while the latter yielded only intense fluorescence, which can be an indication of organic lake pigments, but is not conclusive. A thin, lighter band (d) along the top of the reddish paint layer (c) contains fine lighter red particles (vermilion), while the deeper violet, more transparent particles (estimated to be a lake colorant) are located below the light band. This feature could indicate surface fading of the salmon-colored paint layer in the pants and loss of the organic lake colorant due to light exposure. The difference between (c) and (d) is quite distinctive under normal light, but barely discernible under UV.

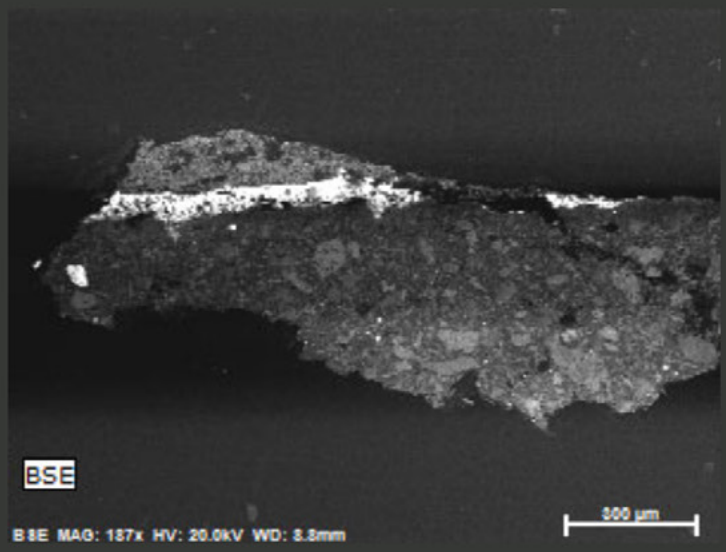
Elemental mapping of the red paint layer confirms the presence of lead white, vermilion or cinnabar (Hg), iron, malachite (Cu), and sulfur (S). There appears to be a thin distribution of calcium (Ca) directly below the paint layer. Phosphorus (P) corresponds to the calcium map in regions of black particles near the top edge of the paint layer that were identified as bone or ivory black ($Ca_3(PO_4)_2$ and C) by Raman spectroscopy.

Cross Section 2 (CS02)

Location: Bottom edge of the soldier's salmon-colored trousers

SEM-EDS MAPS

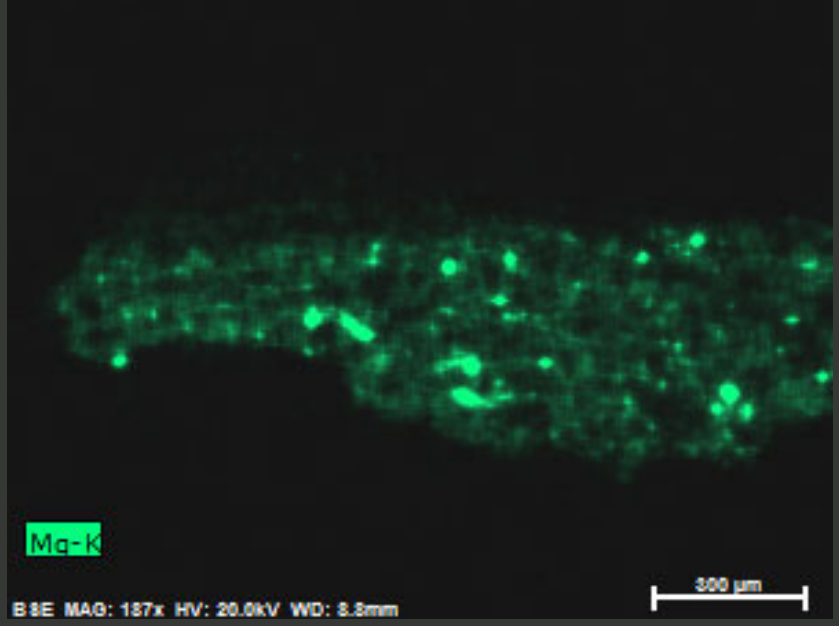
BSE
Mg
Al
Si
P
S
K
Ca
Ti
Fe
Cu
Hg
Pb

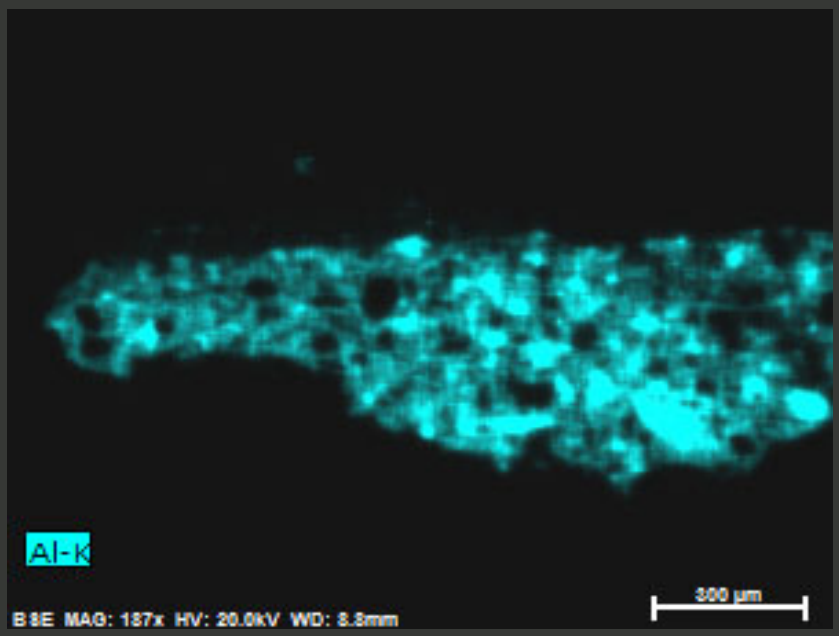


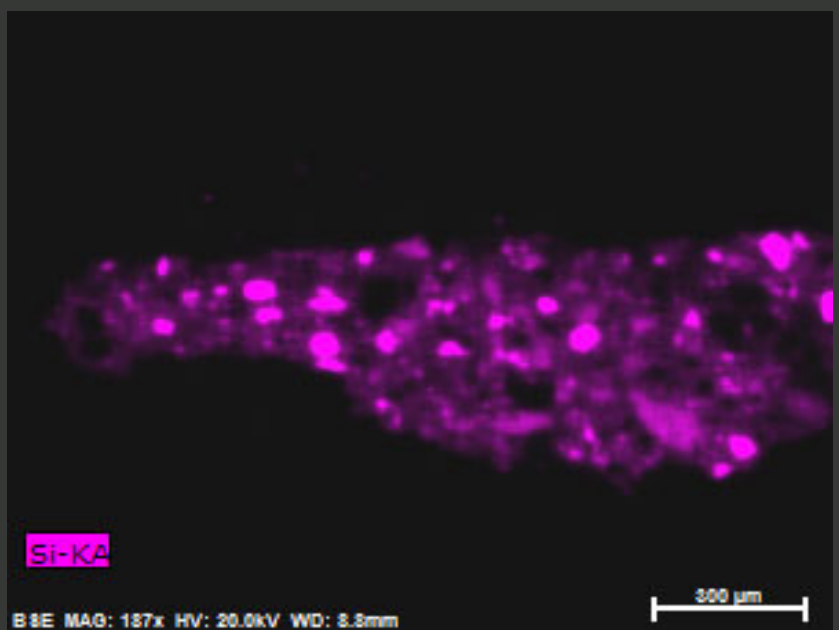
MAG: 187x
HV: 20 kV
WD: 8.8 mm
Scale bar: 300 µm

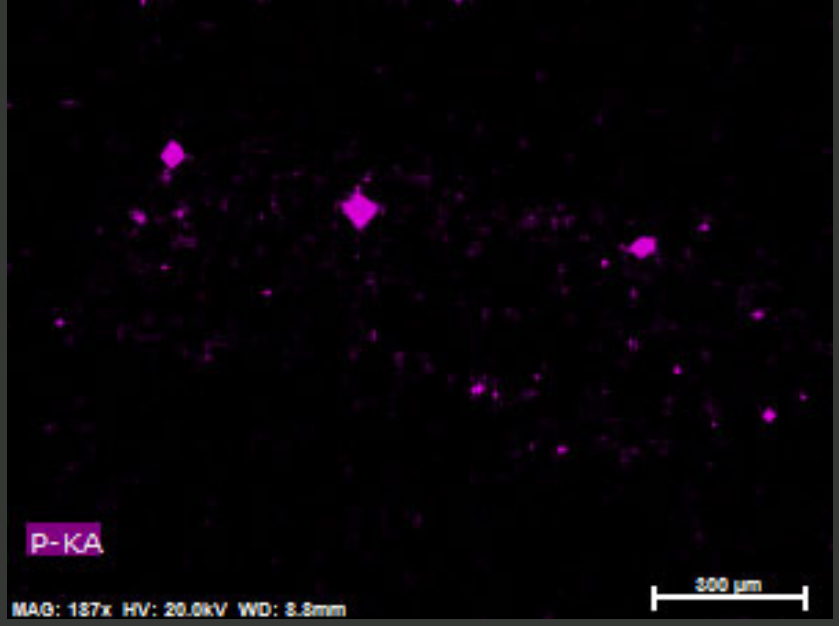
SURFACE COATINGS

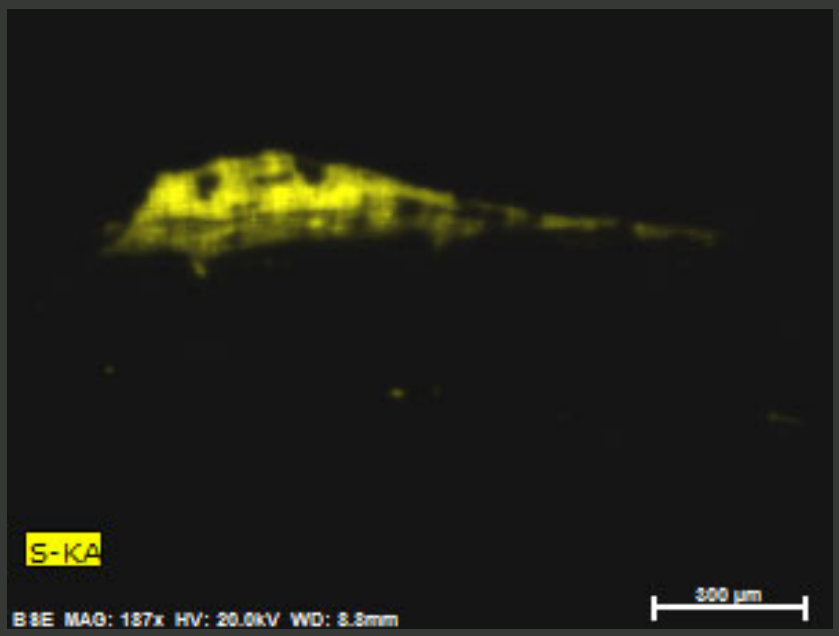
When viewed under UV irradiation, five separate layers can be distinguished on top of the faded paint layer. At the top is the outer encapsulation layer (i). Below the encapsulation layer is a strongly fluorescing layer (h), later verified with Fourier-transform infrared spectroscopy (FTIR) as shellac. A thin layer of retouching (g) directly below the shellac is interspersed with black particles, identified as ivory or bone black by Raman spectroscopy. A thick band of gypsum ($CaSO_4 H_2 O$) fill material (f) is located between the black overpaint and the original paint layers; see elemental maps of calcium (bottom right) and sulfur (middle of second row). Under normal light, a fairly transparent light brown layer with some scattered pigment particles

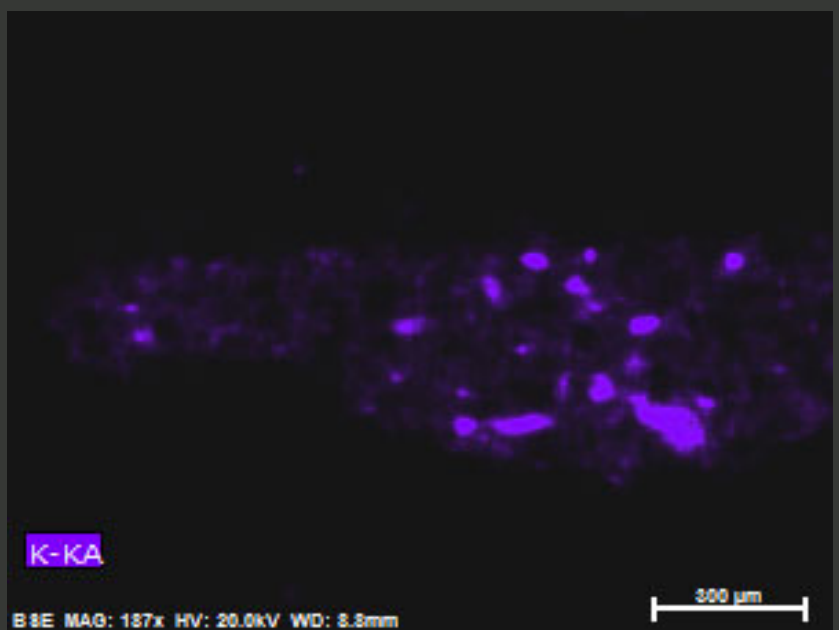

Mg-K
B 8E MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm

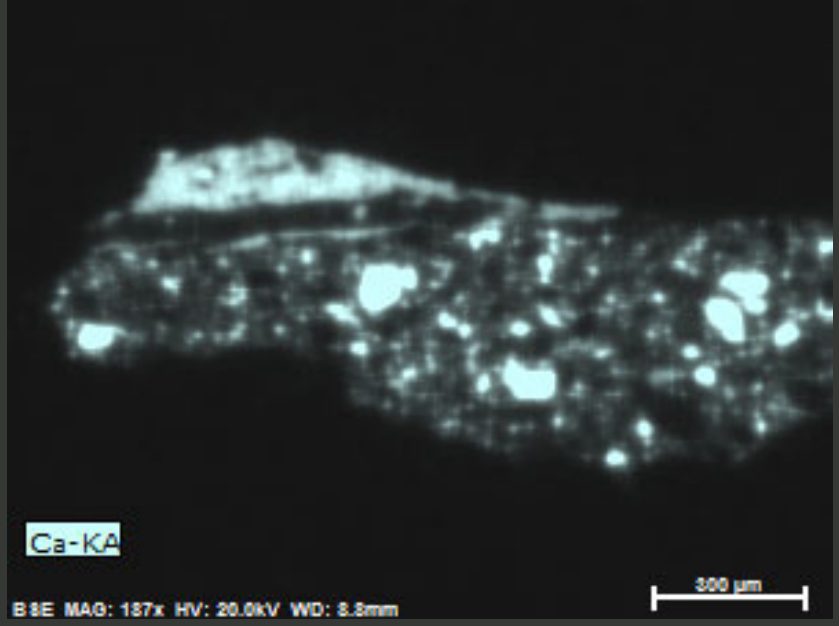

Al-K
B 8E MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm

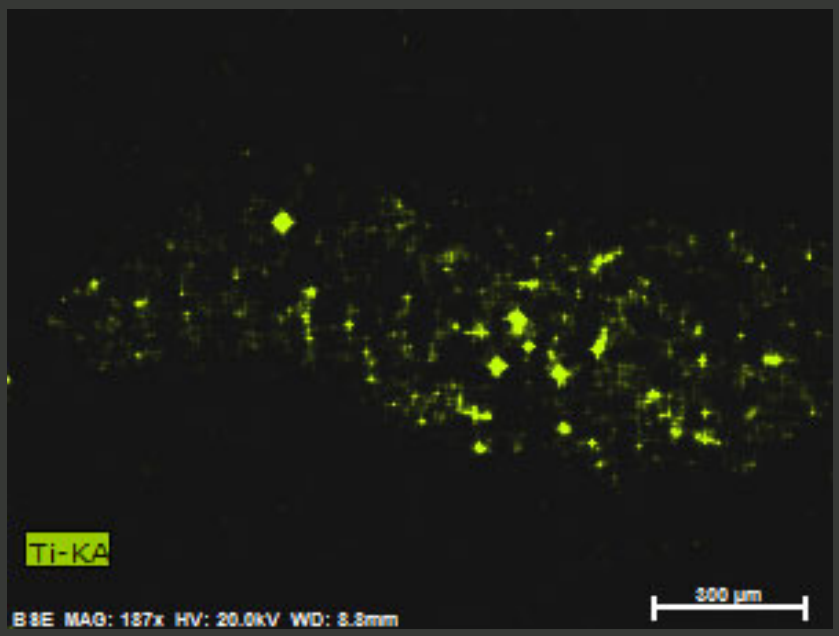

Si-KA
B 8E MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm

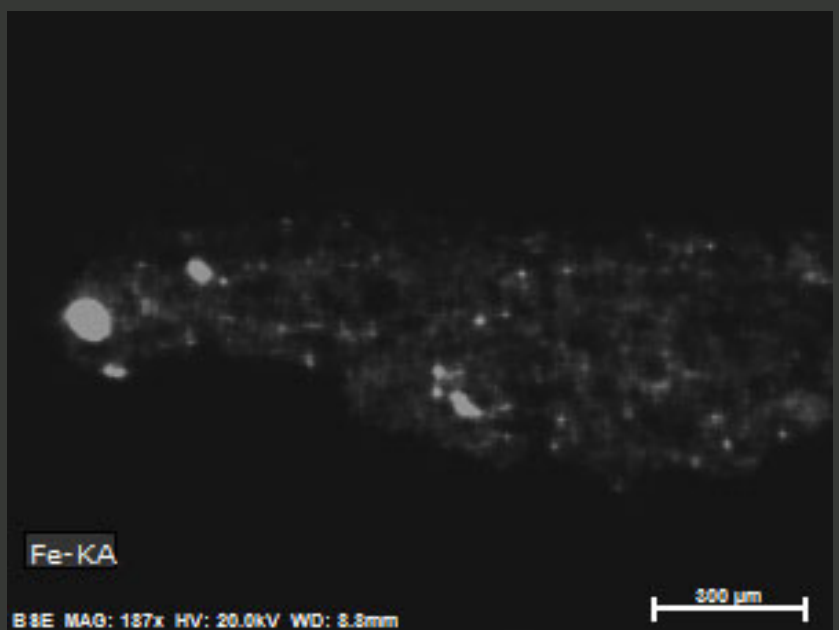

P-KA
MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm


S-KA
BSE MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm


K-KA
BSE MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm


Ca-KA
B 8E MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm


Ti-KA
B 8E MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm

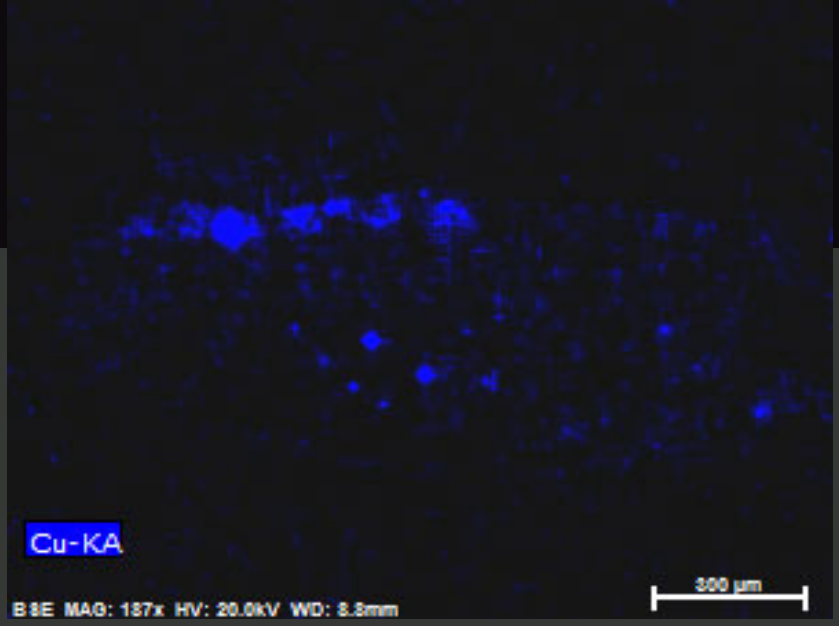

Fe-KA
B 8E MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm

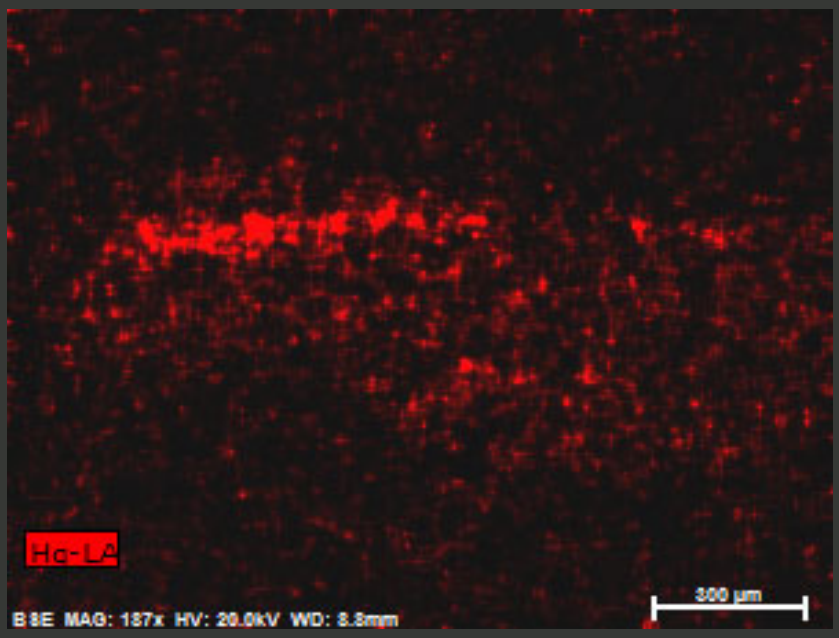
Cross Section 2 (CS02)

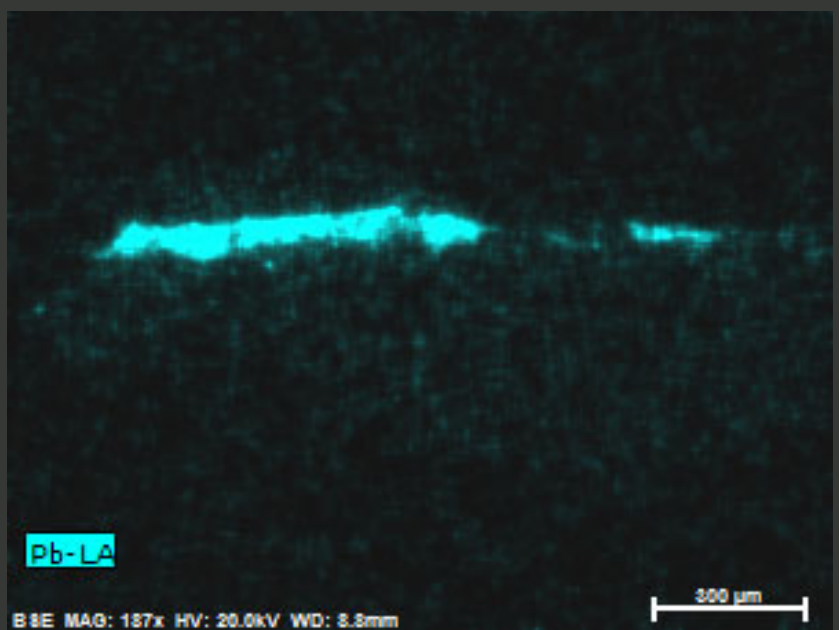
Location: Bottom edge of the soldier's salmon-colored trousers

SURFACE COATINGS

When viewed under UV irradiation, five separate layers can be distinguished on top of the faded paint layer. At the top is the outer encapsulation layer (i). Below the encapsulation layer is a strongly fluorescing layer (h), later verified with Fourier-transform infrared spectroscopy (FTIR) as shellac. A thin layer of retouching (g) directly below the shellac is interspersed with black particles, identified as ivory or bone black by Raman spectroscopy. A thick band of gypsum ($CaSO_4\,H_2\,O$) fill material (f) is located between the black overpaint and the original paint layers; see elemental maps of calcium (bottom right) and sulfur (middle of second row). Under normal light, a fairly transparent light brown layer with some scattered pigment particles (e) is in direct contact with the paint layer. This layer has a faint yellow-green fluorescence when viewed under UV and may be an early surface coating.


Cu-KA
B 8E MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm

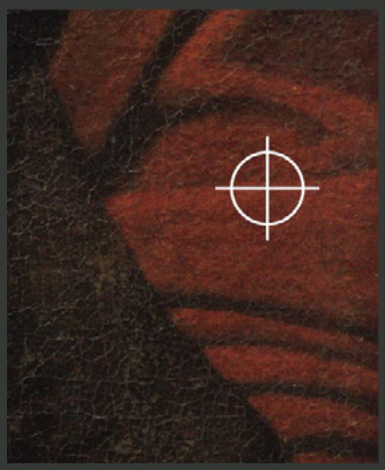

Hg-LA
B 8E MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm

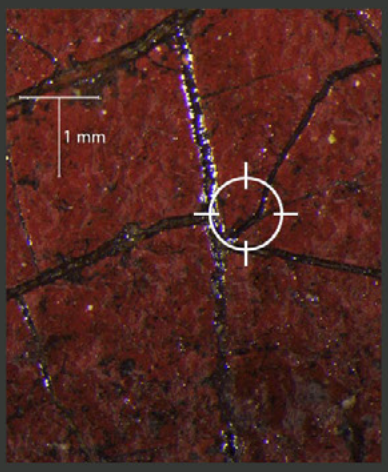

Pb-LA
B 8E MAG: 187x HV: 20.0kV WD: 8.8mm
300 µm

Cross Section 3 (CS03)

Location: Highlight in dark fold of the red garment of the figure on the right

The sample was taken after completion of the treatment to determine the composition of the red paint layer. XRF indicated the presence of lead in highlights of the red garment. SEM-EDS identified the red pigment.



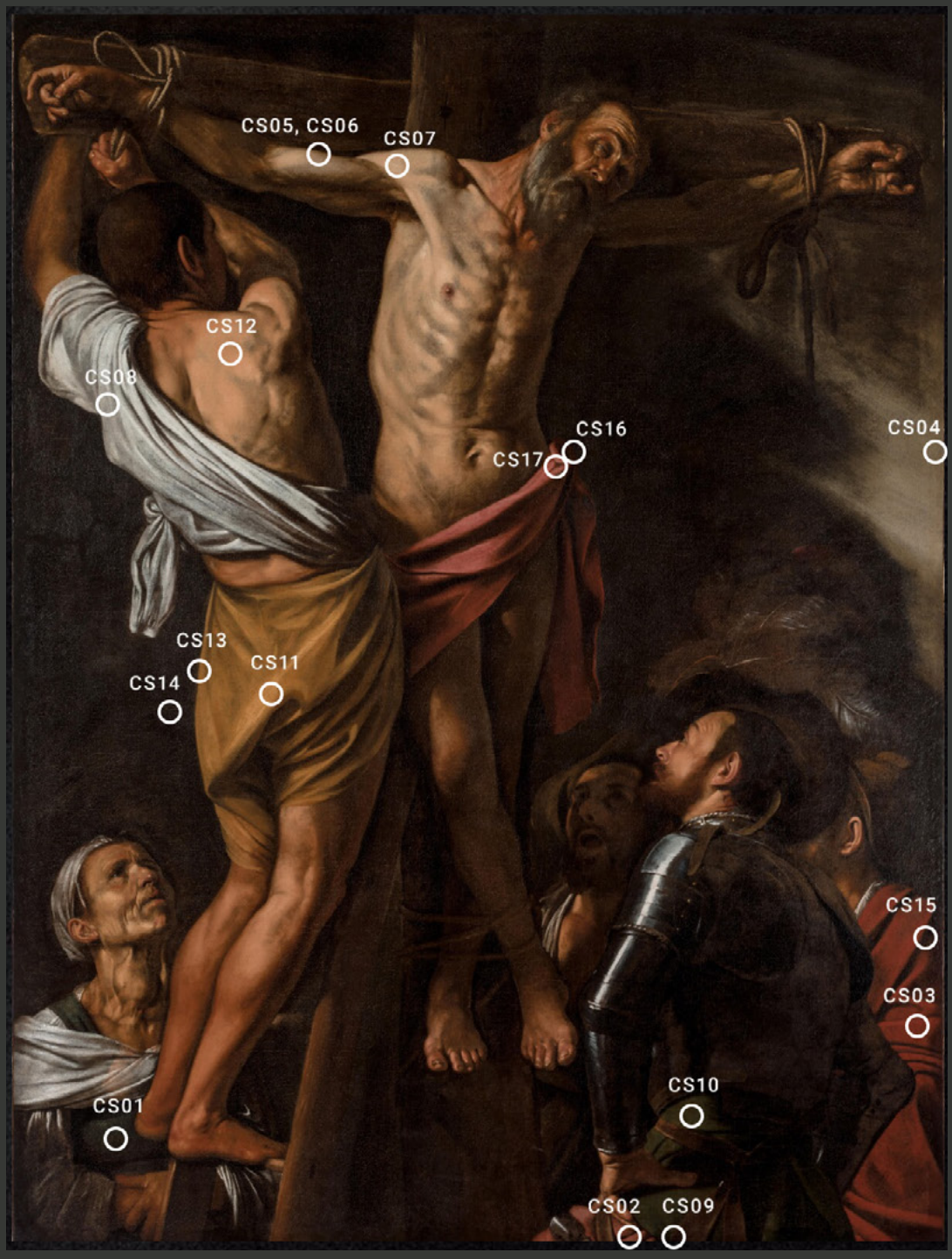


CROSS SECTIONS

GROUND LAYERS

RAMAN SPECTROSCOPY

PAINT LAYERS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

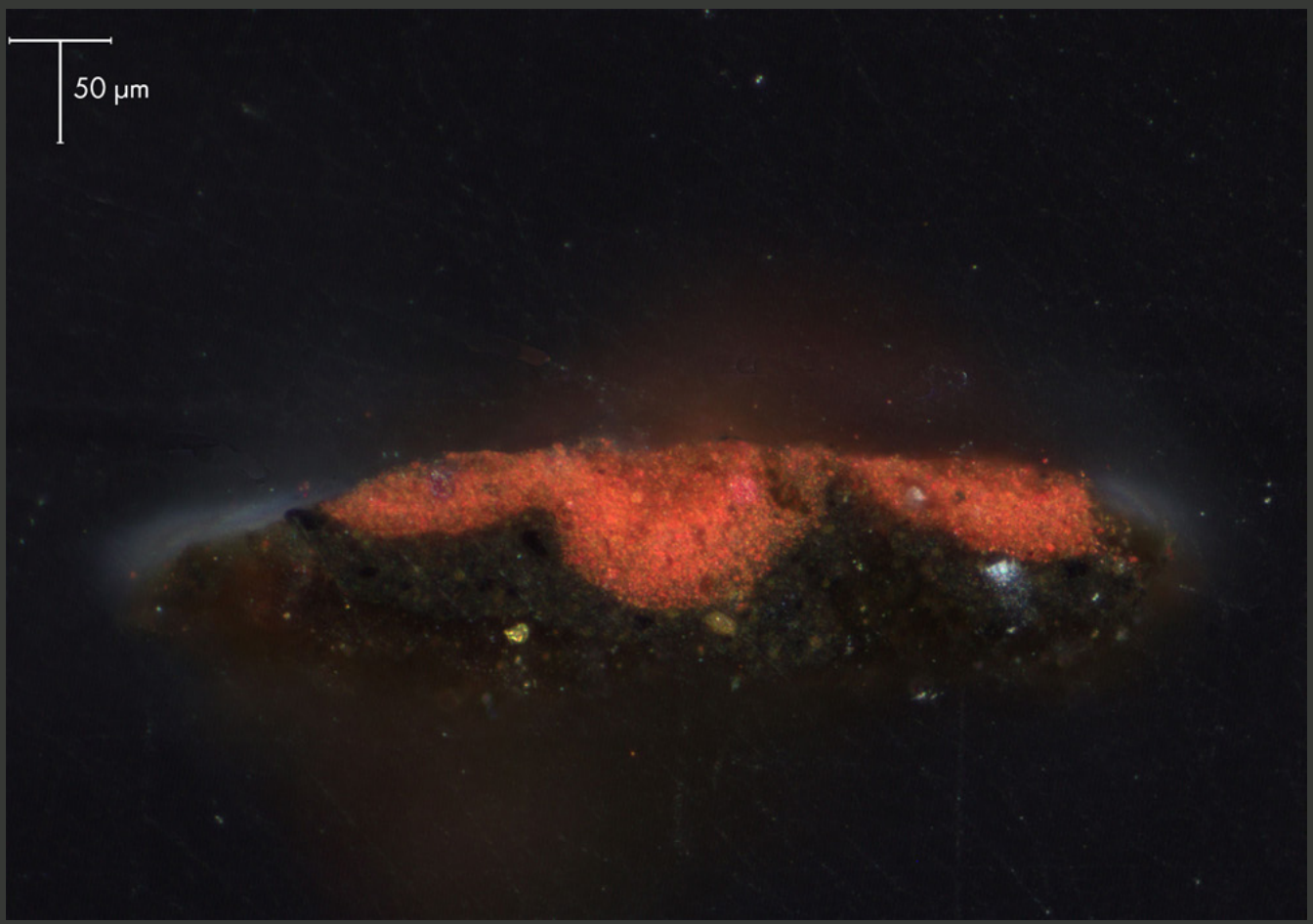
Cross Section 3 (CS03)

Location: Highlight in dark fold of the red garment of the figure on the right

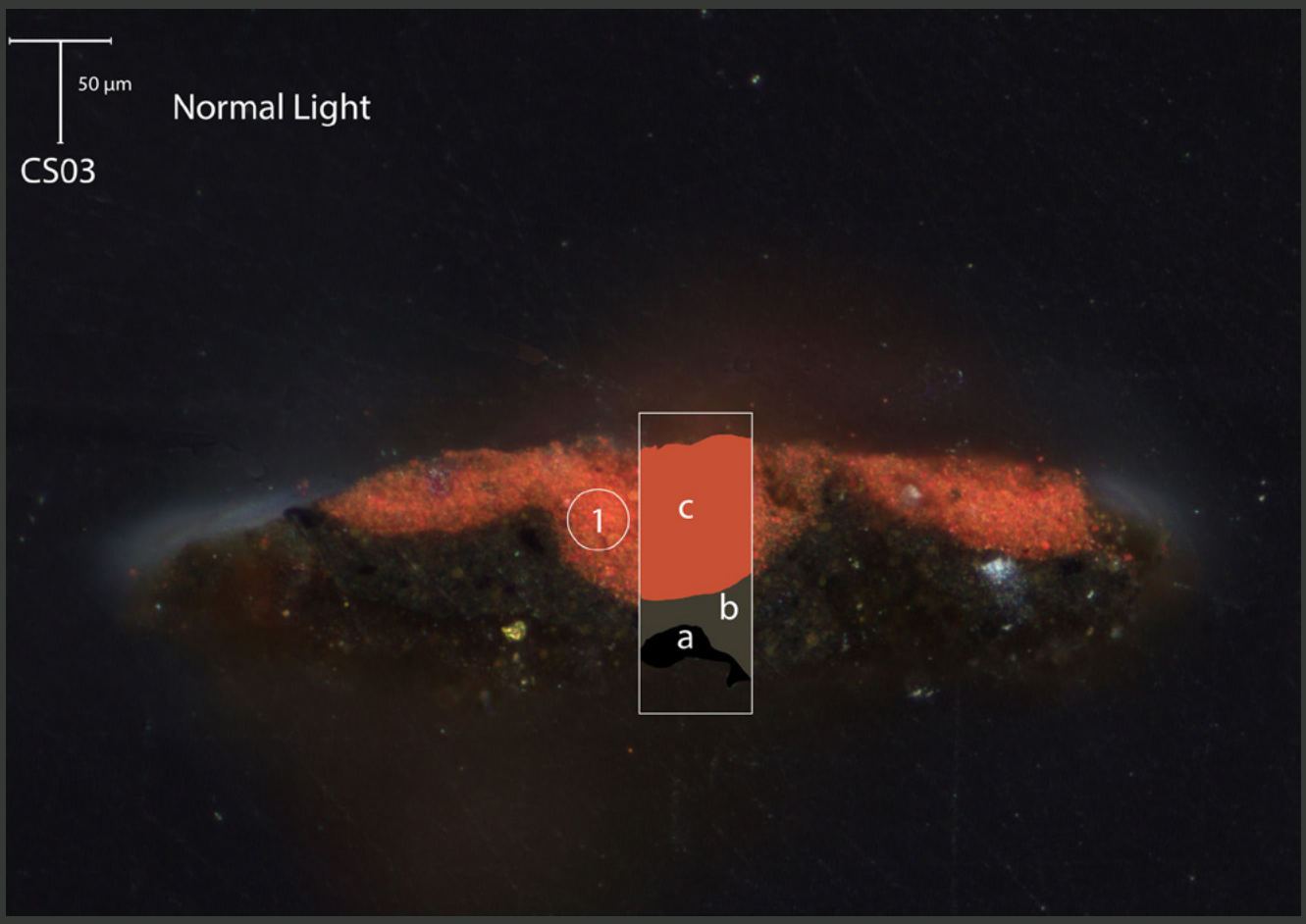
The sample was taken after completion of the treatment to determine the composition of the red paint layer. XRF indicated the presence of lead in highlights of the red garment. SEM-EDS identified the red pigment.

CROSS SECTIONS

Normal Light Overlay



Layer c: red paint layer confirmed as hematite by Raman spectroscopy
Layer b: underlying black layer confirmed as carbon black by Raman spectroscopy
Layer a: top (oil-bound) ground layer
Note: The lower (glue-bound) ground is missing from this sample.



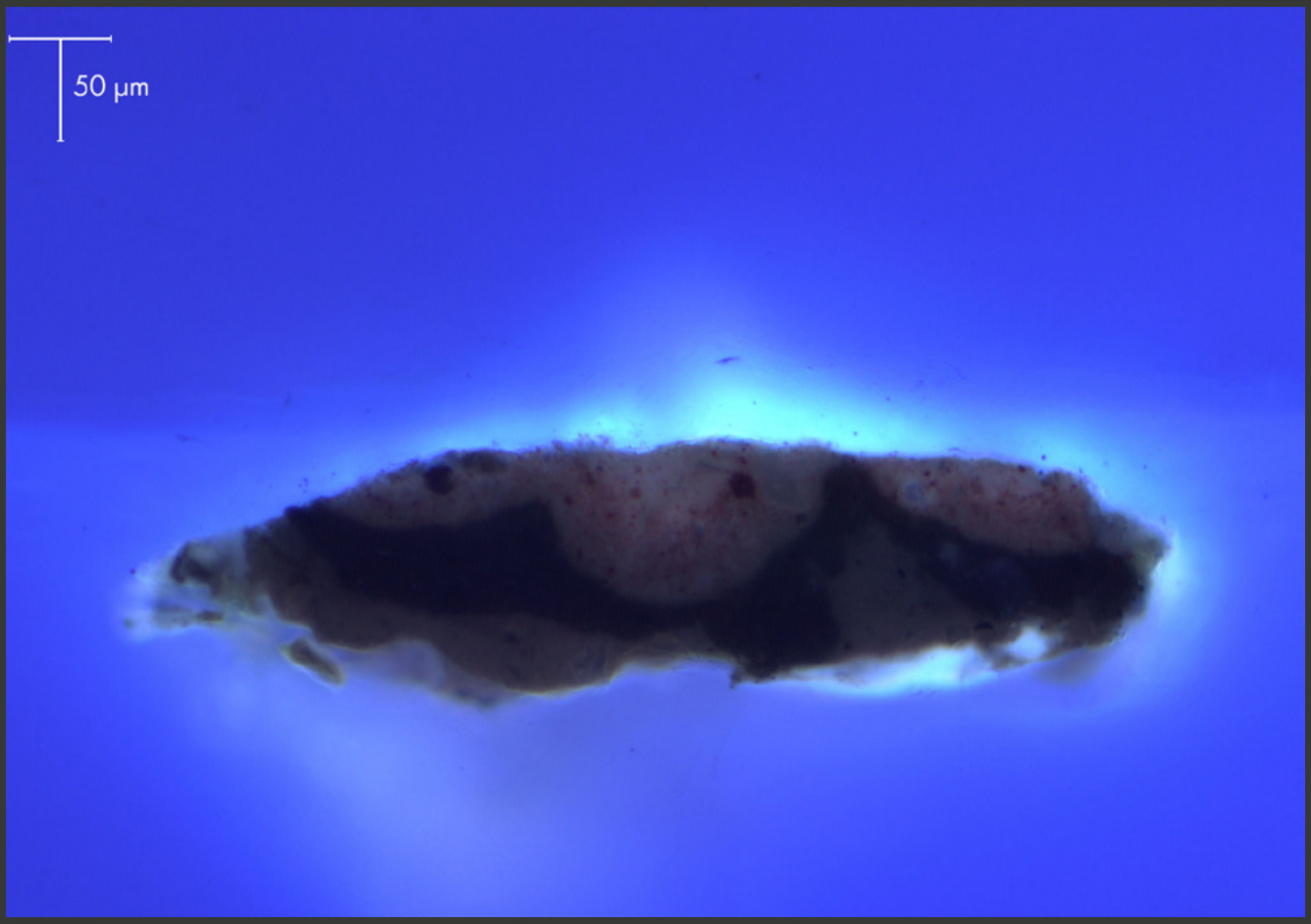
Cross Section 3 (CS03)

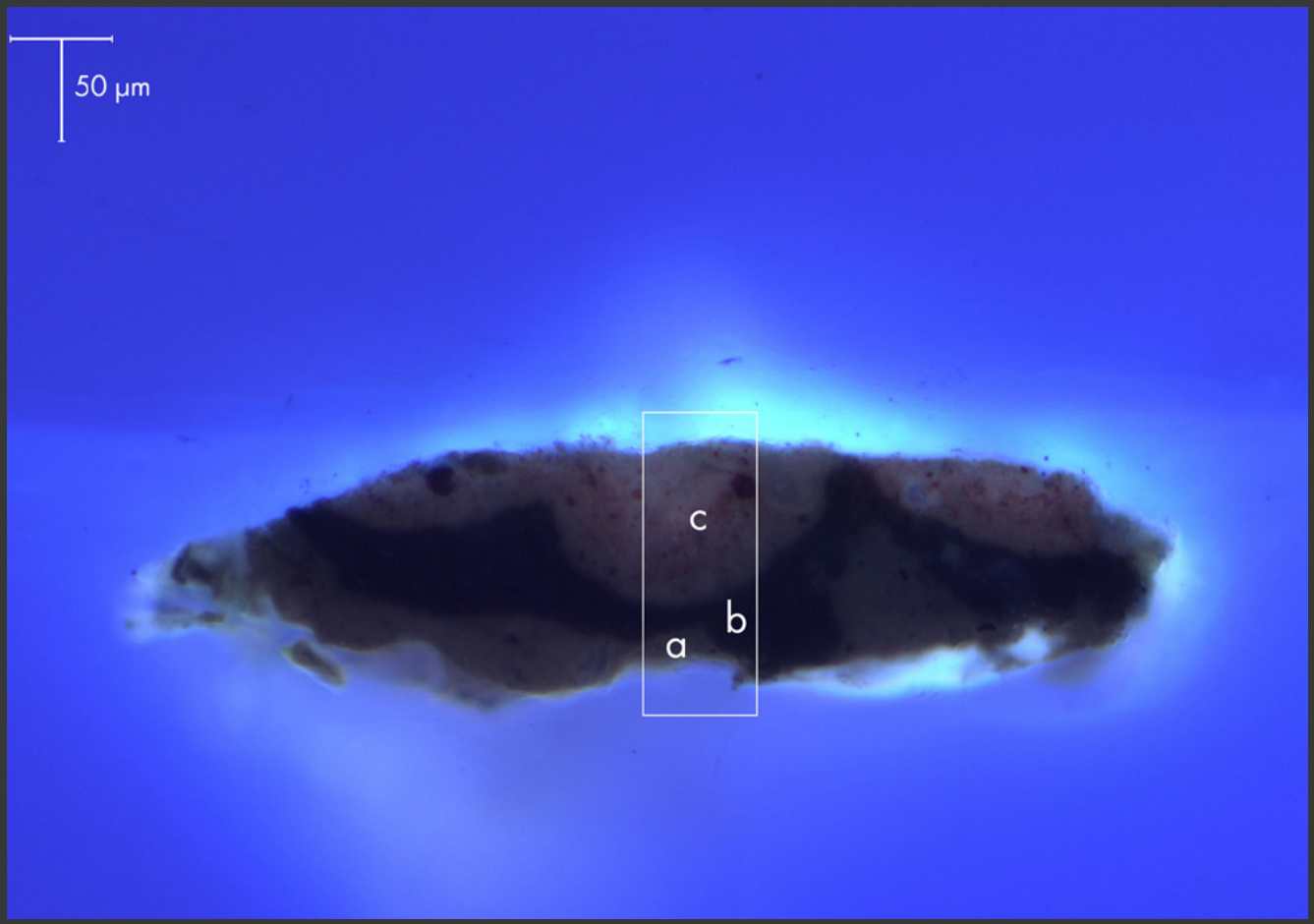
Location: Highlight in dark fold of the red garment of the figure on the right

Layer c: red paint layer confirmed as hematite by Raman spectroscopy
Layer b: underlying black layer confirmed as carbon black by Raman spectroscopy
Layer a: top (oil-bound) ground layer
Note: The lower (glue-bound) ground is missing from this sample.

Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm)

Overlay



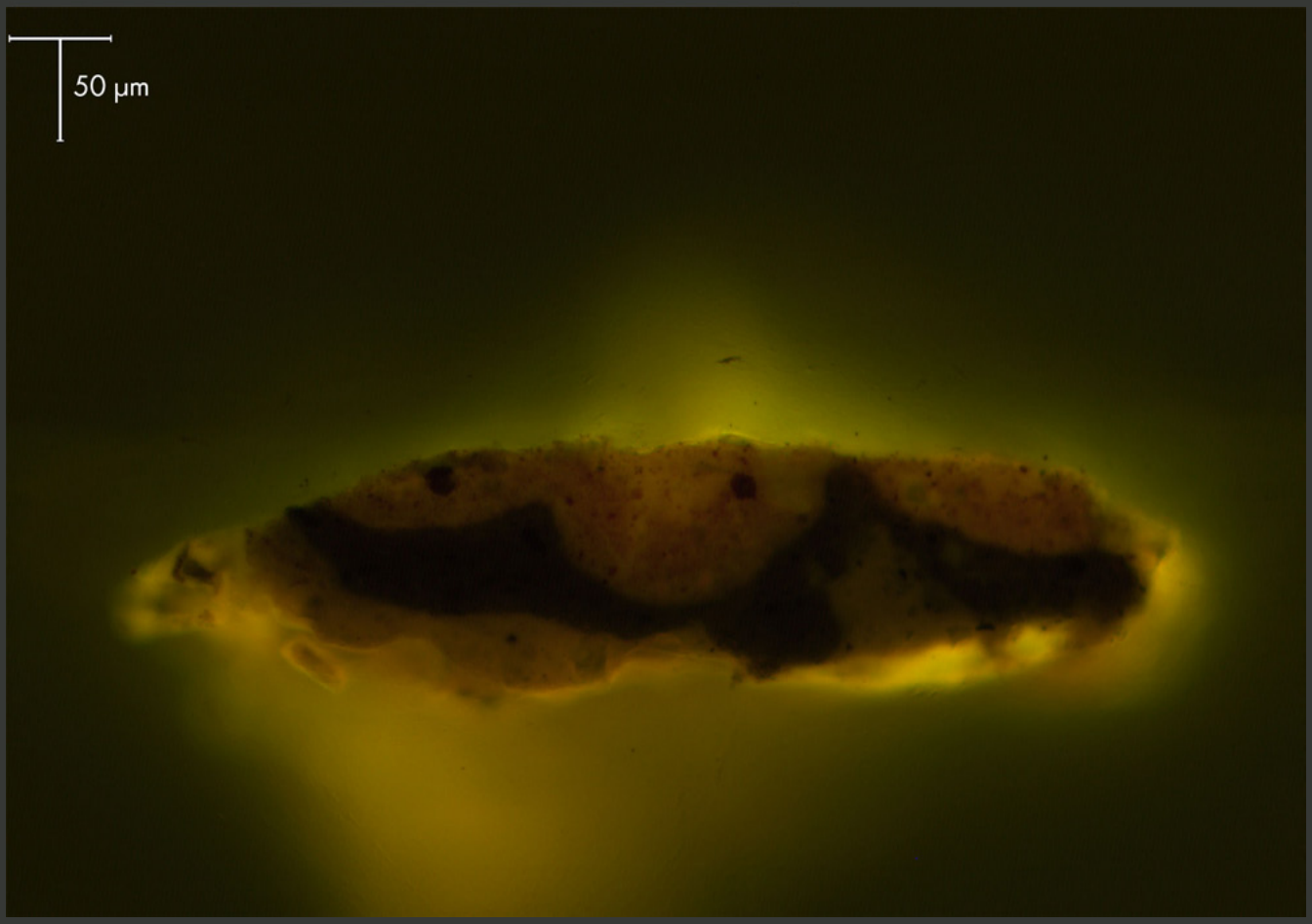

50 µm
c
b
a

Cross Section 3 (CS03)

Location: Highlight in dark fold of the red garment of the figure on the right

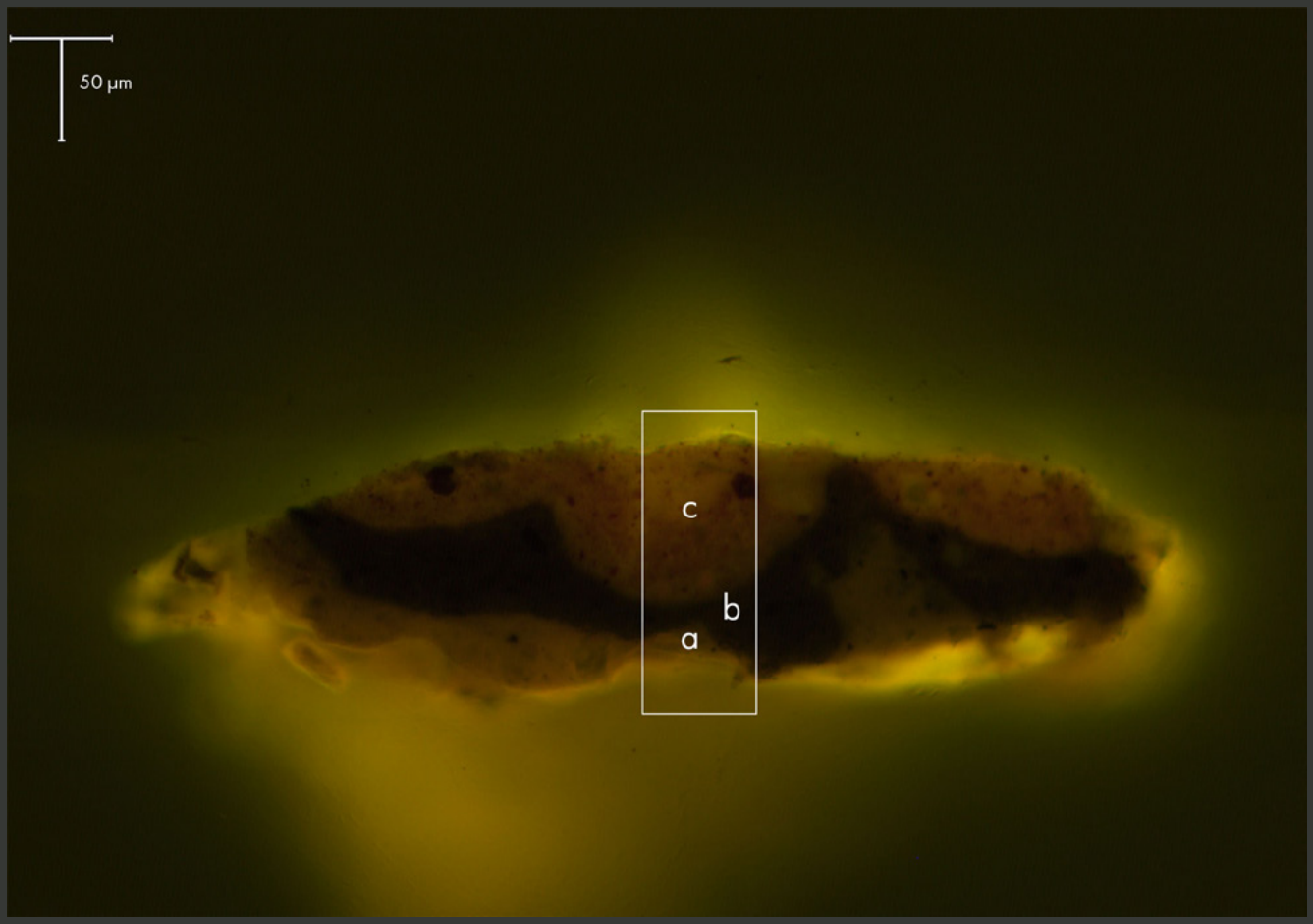
Excitation: blue (450–490 nm)
Emission: green (λ_{em} > 515 nm)

Overlay



GROUND LAYERS

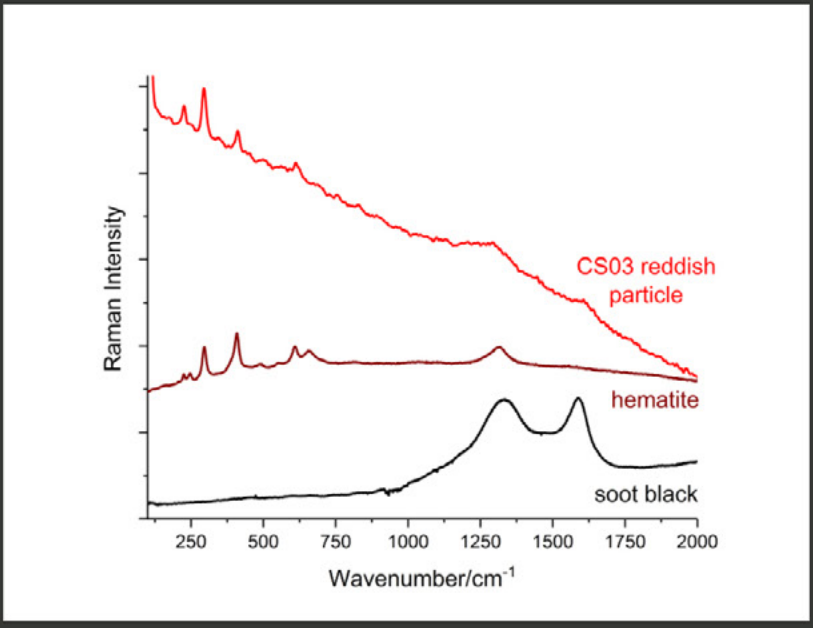
Only the upper ground (a) was retained during sample removal; the lower ground remained adhered to the canvas.


50 µm
c
b
a

Cross Section 3 (CS03)

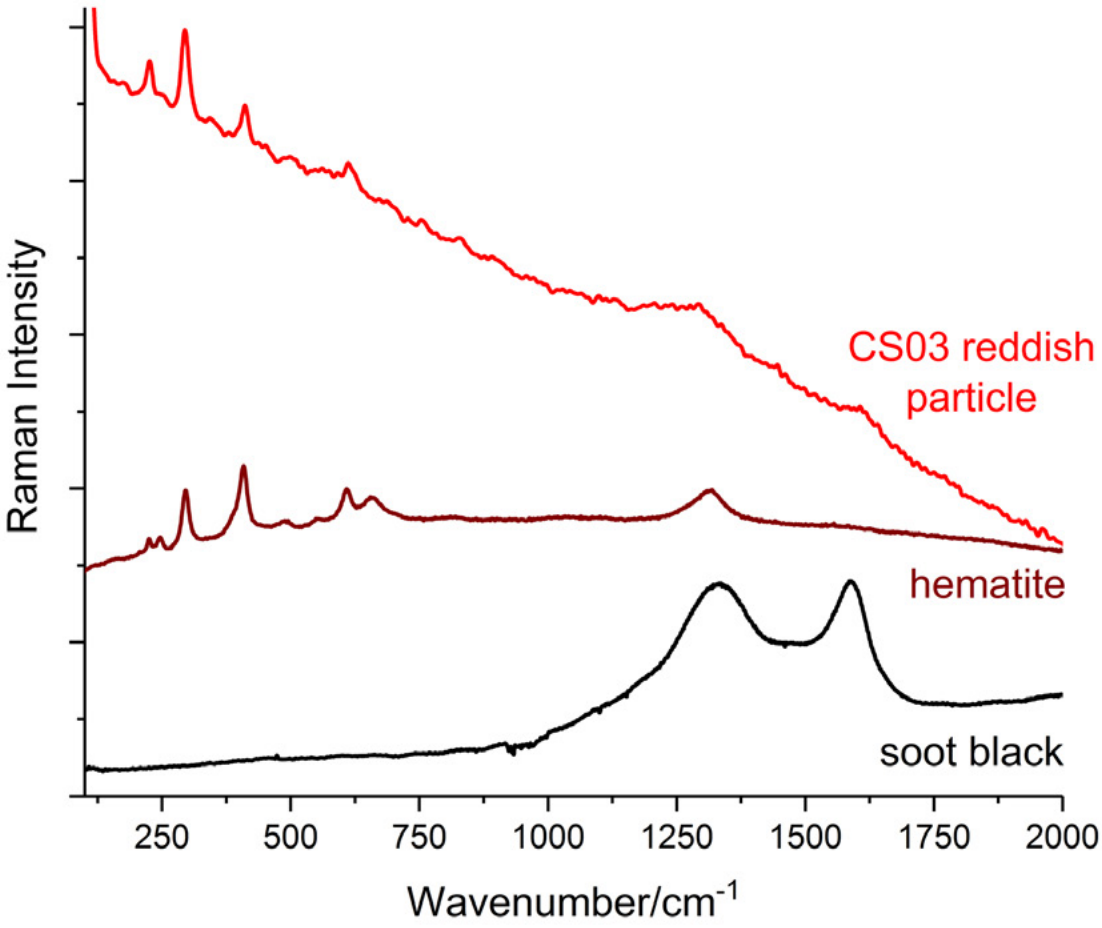
Location: Highlight in dark fold of the red garment of the figure on the right

RAMAN SPECTROSCOPY



PAINT LAYERS

XRF spectra from the same area of the paint surface showed intense lead and iron peaks. The red color of the paint layer and the XRF spectrum suggested the possibility of minium, or red lead, pigment (Pb_3O_4). However, layer (c), location 1, of the sample was later identified as hematite (Fe_2O_3, red ochre) with Raman spectroscopy. The intense indication of lead in the XRF analysis can be traced to the finely dispersed particles of lead white that are intermixed with the hematite. Black particles located within the underlying dark gray-brown layer (b) were identified by Raman analysis as soot or carbon black. SEM-EDS analysis was not conducted on this sample.


Raman Intensity
CS03 reddish particle
hematite
soot black
250
500
750
1000
1250
1500
1750
2000
Wavenumber/cm-1

Cross Section 4 (CS04)

Location: Beam of light from the right edge

This sample, taken before cleaning, was primarily used to image the pretreatment varnish structure.

CROSS SECTIONS

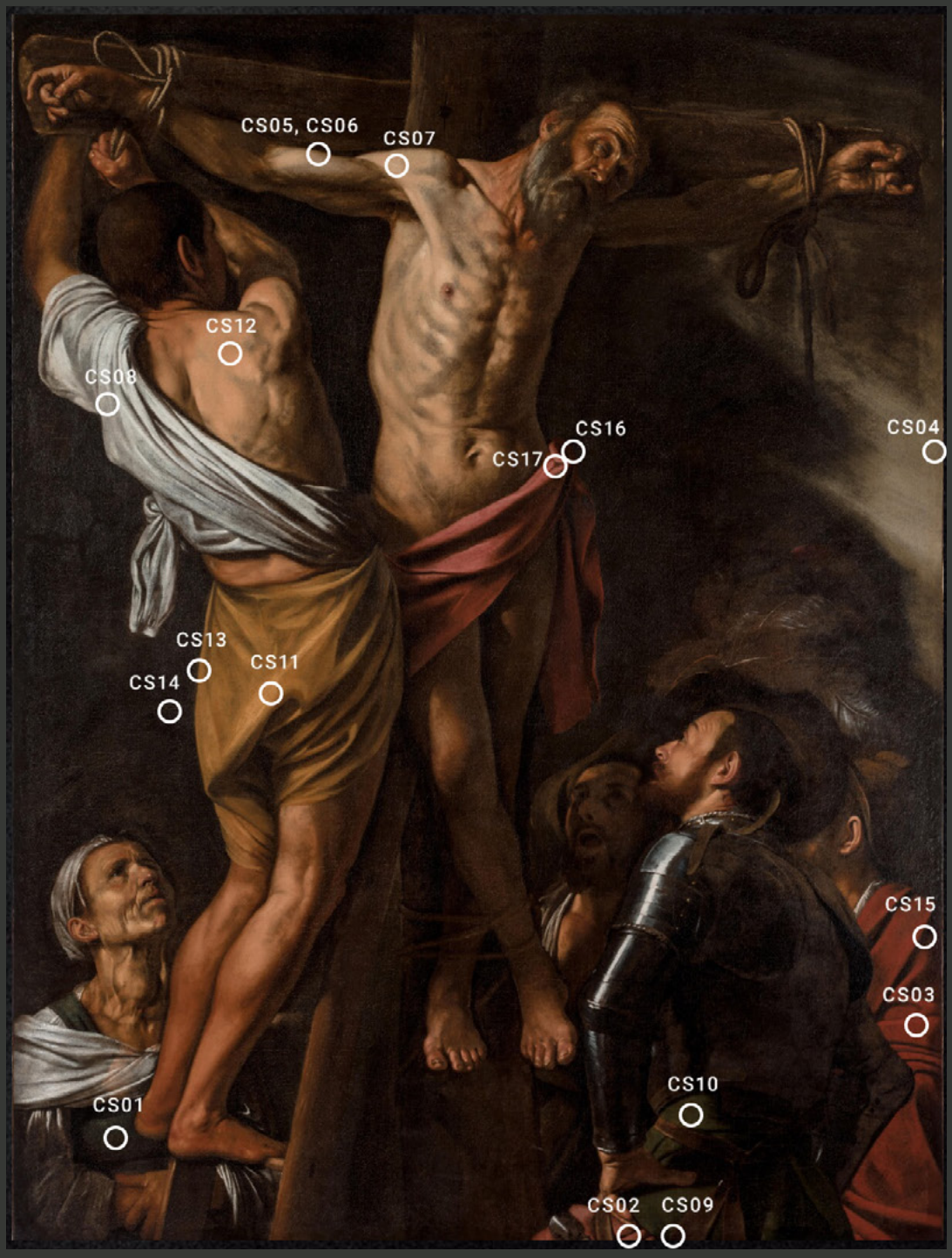
GROUND AND PAINT LAYERS

UV DETAIL

CROSS SECTIONS

GROUND AND PAINT LAYERS

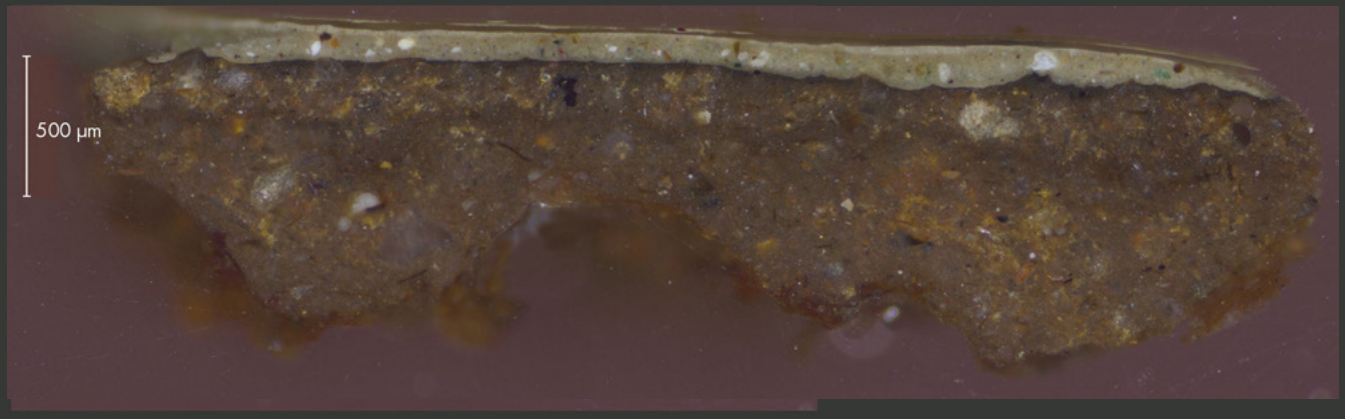
UV DETAIL


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

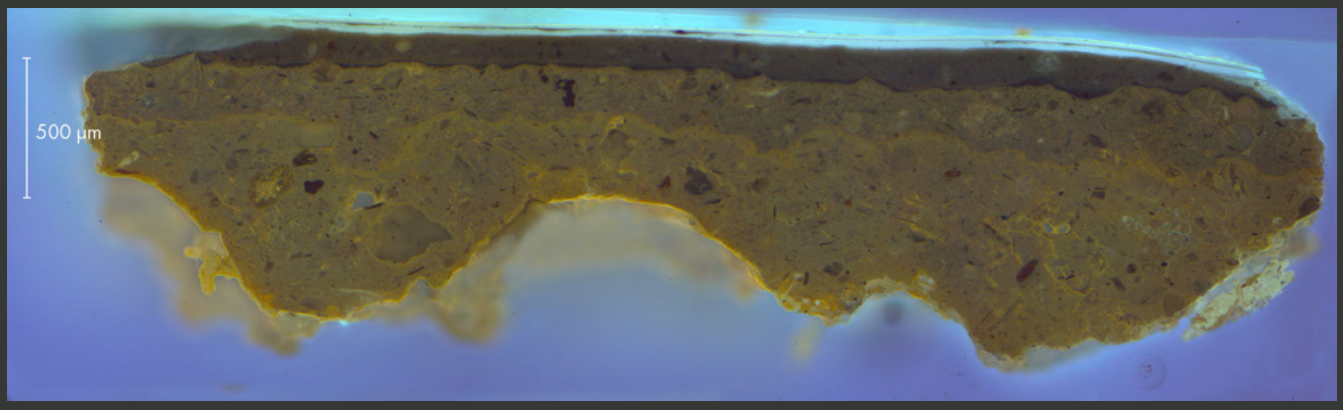
Cross Section 4 (CS04)

CROSS SECTIONS

Normal Light Overlay

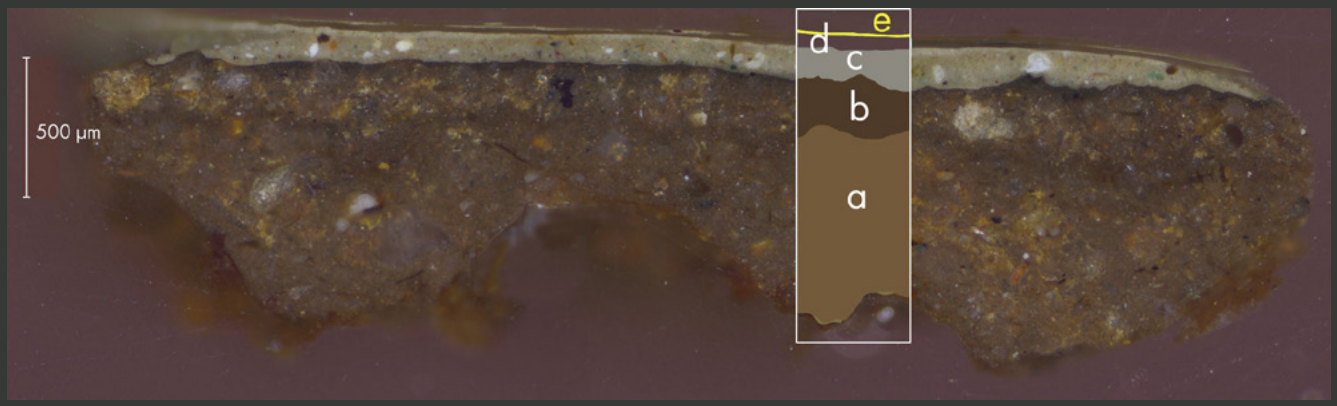


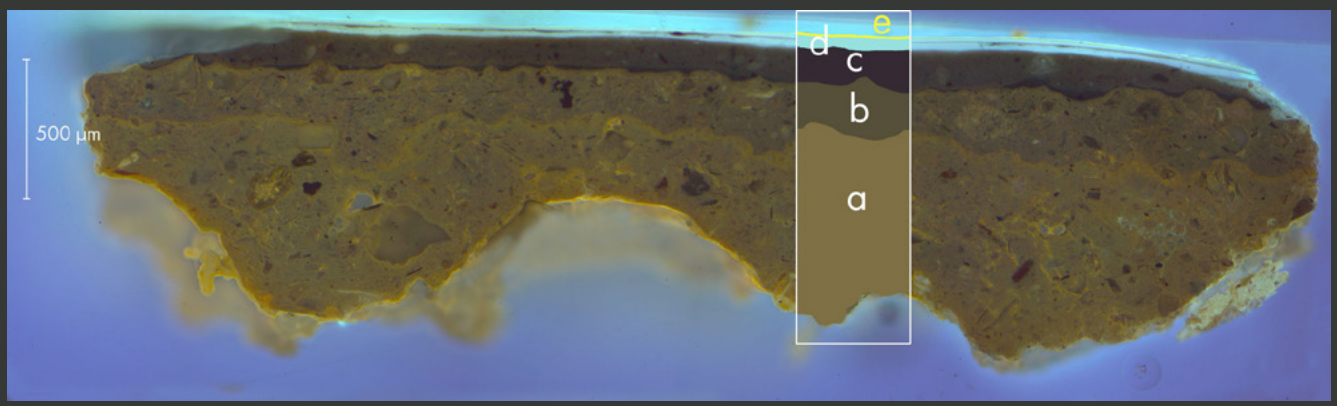
Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm) Overlay



GROUND AND PAINT LAYERS

This cross section also clearly illustrates the thick construction of the lower ground (a) used to fill in the coarse structure of the raised warp float weave. In fact, the recess in the center of the lower ground (a) is likely the space previously occupied by a canvas thread. The upper ground (b) is slightly darker than the lower ground when viewed under UV. EDS elemental mapping of the pigments used in the ground was not conducted on this sample (cross section 2 provides this information). The light gray paint layer (c) contains numerous pigment particles that require future analysis.

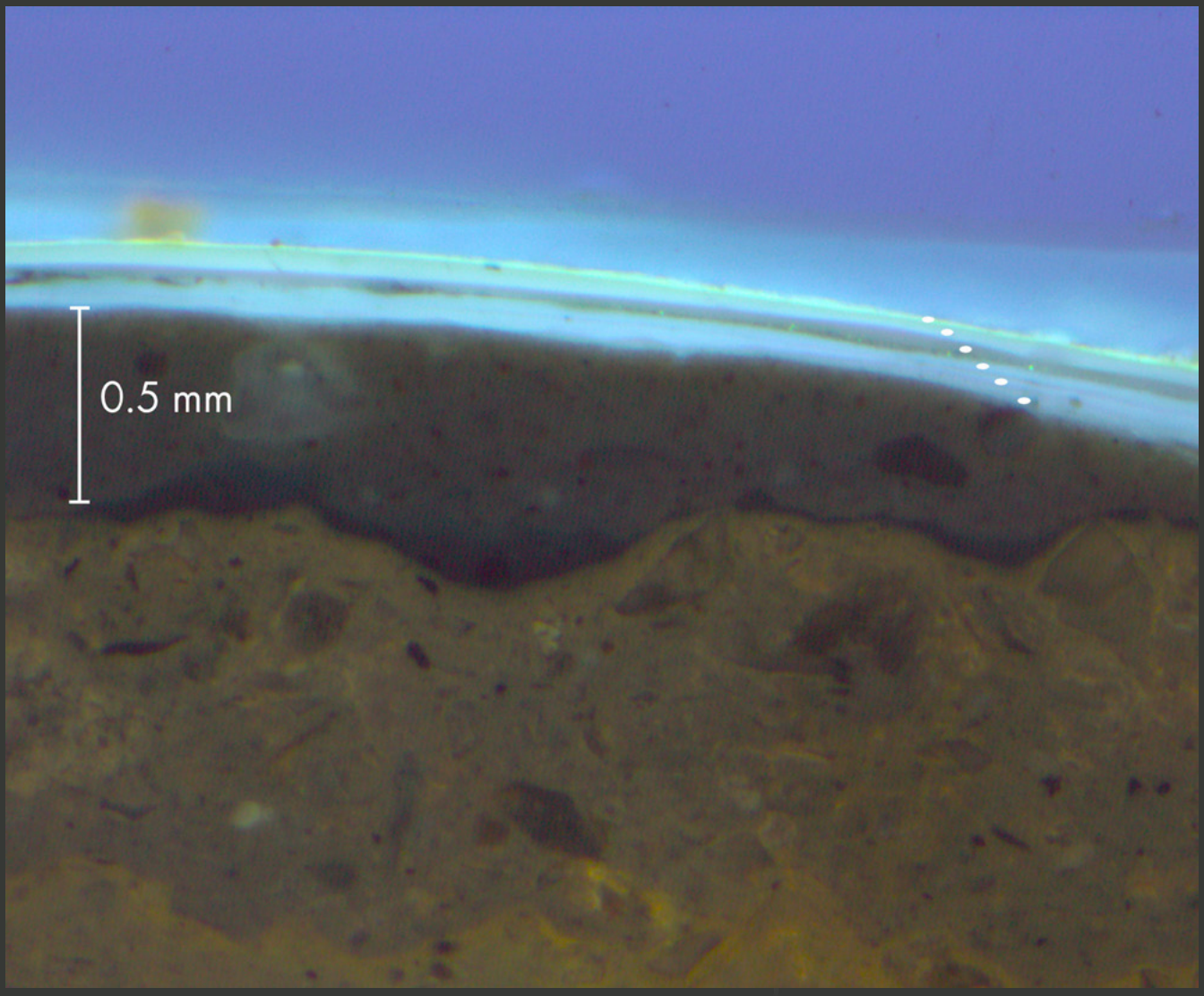

500 µm
e
d
c
b
a


500 µm
e
d
c
b
a

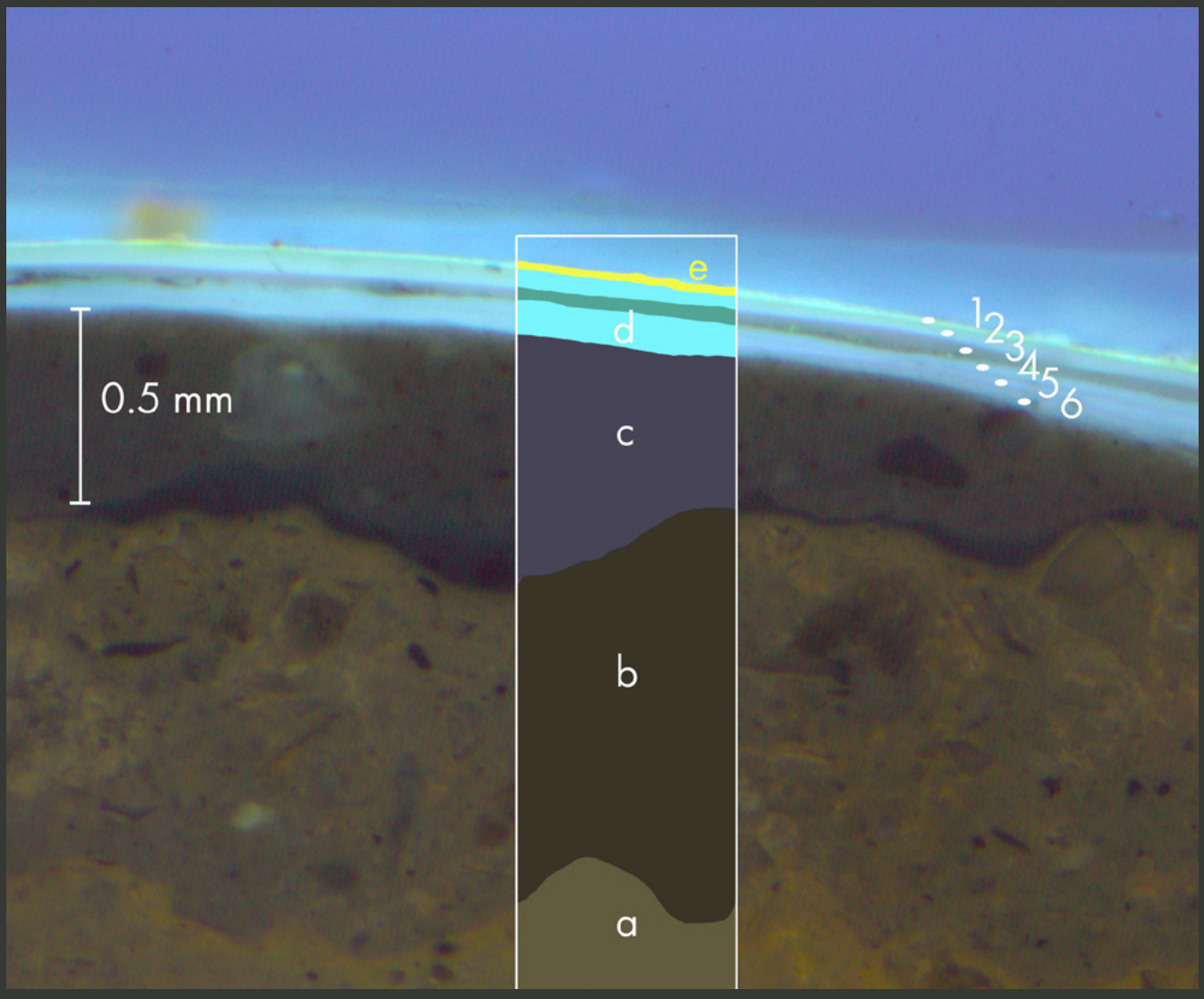
UV DETAIL

Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm)

Overlay

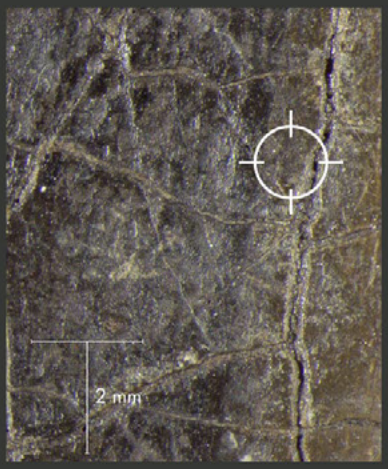


Multiple layers of Griffin varnish (d-2 and d-4–6) are located below a brightly fluorescing yellow-green top layer (e-1) identified as shellac using FTIR spectroscopy. A layer of oil-based retouching (d-3) is sandwiched between layers of Griffin varnish. A similar buildup of varnish and retouching was found throughout the painting during the initial cleaning tests and in photomicrographs of the varnish surface.


0.5 mm
e
d
c
b
a
1
2
3
4
5
6

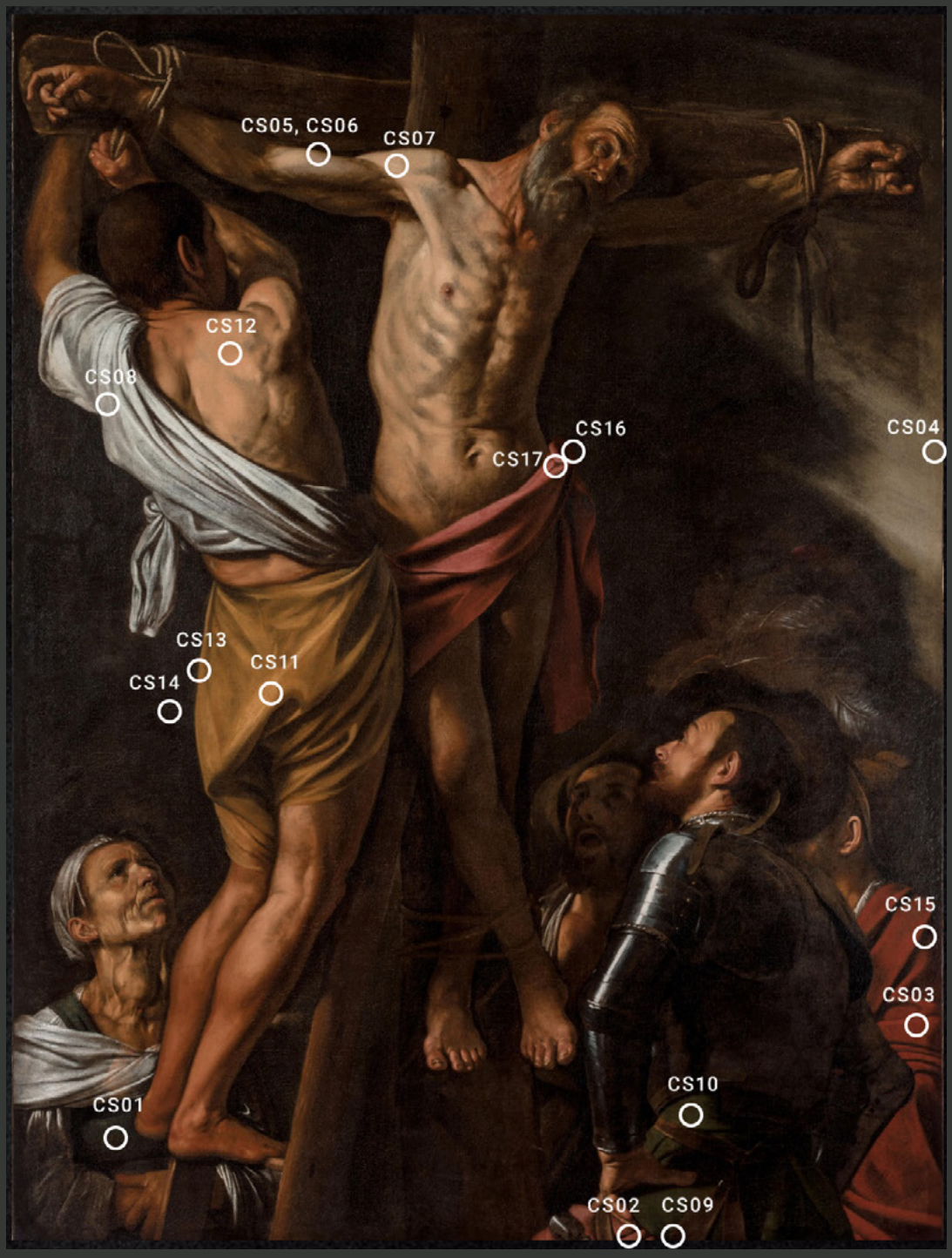
Cross Section 5 & 6 (CS05 & CS06)

Location: Saint Andrew's right bicep muscle



CROSS SECTIONS CS05

CROSS SECTIONS CS06


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

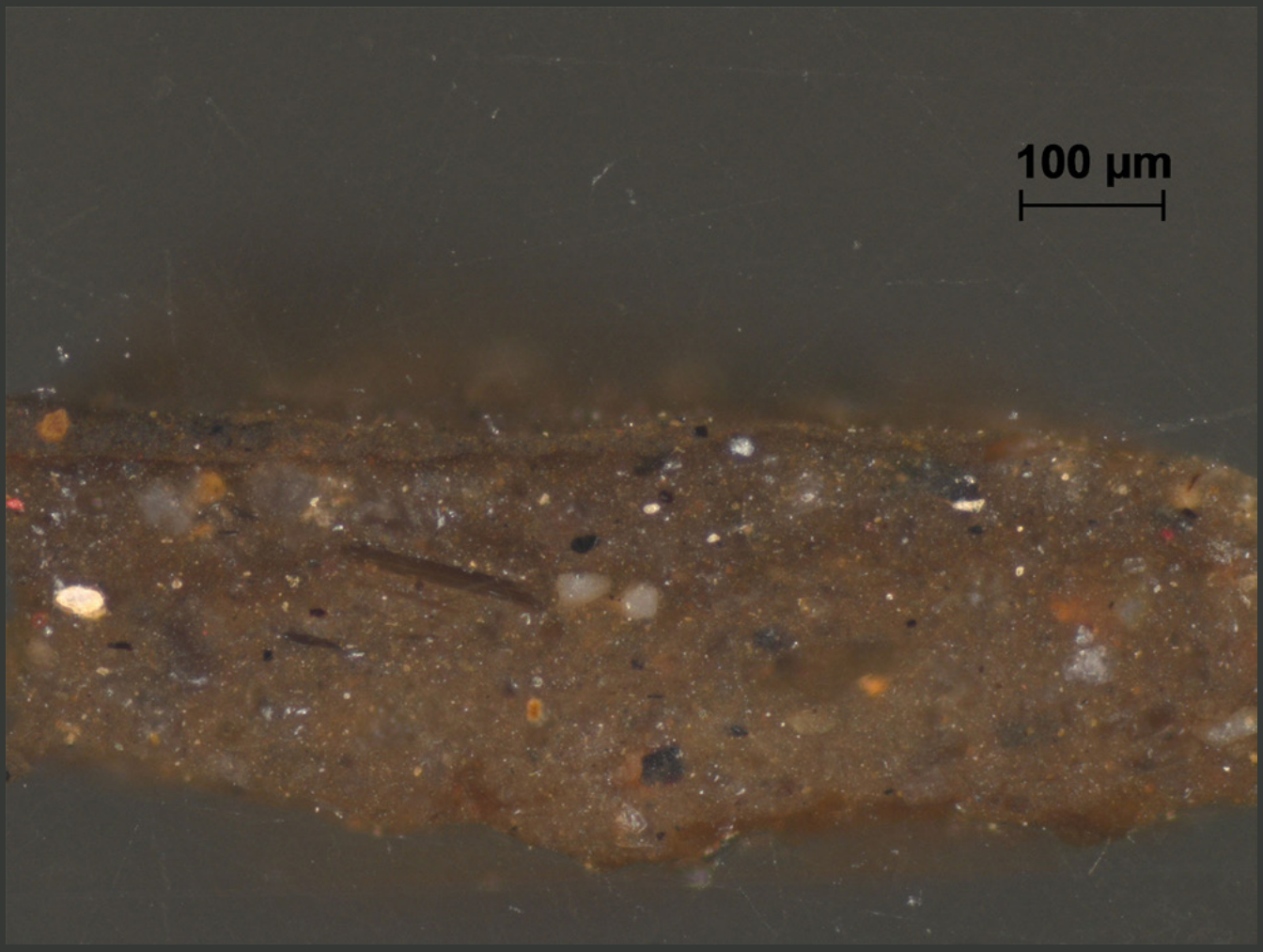
Cross Section 5 & 6 (CS05 & CS06)

Location: Saint Andrew's right bicep muscle

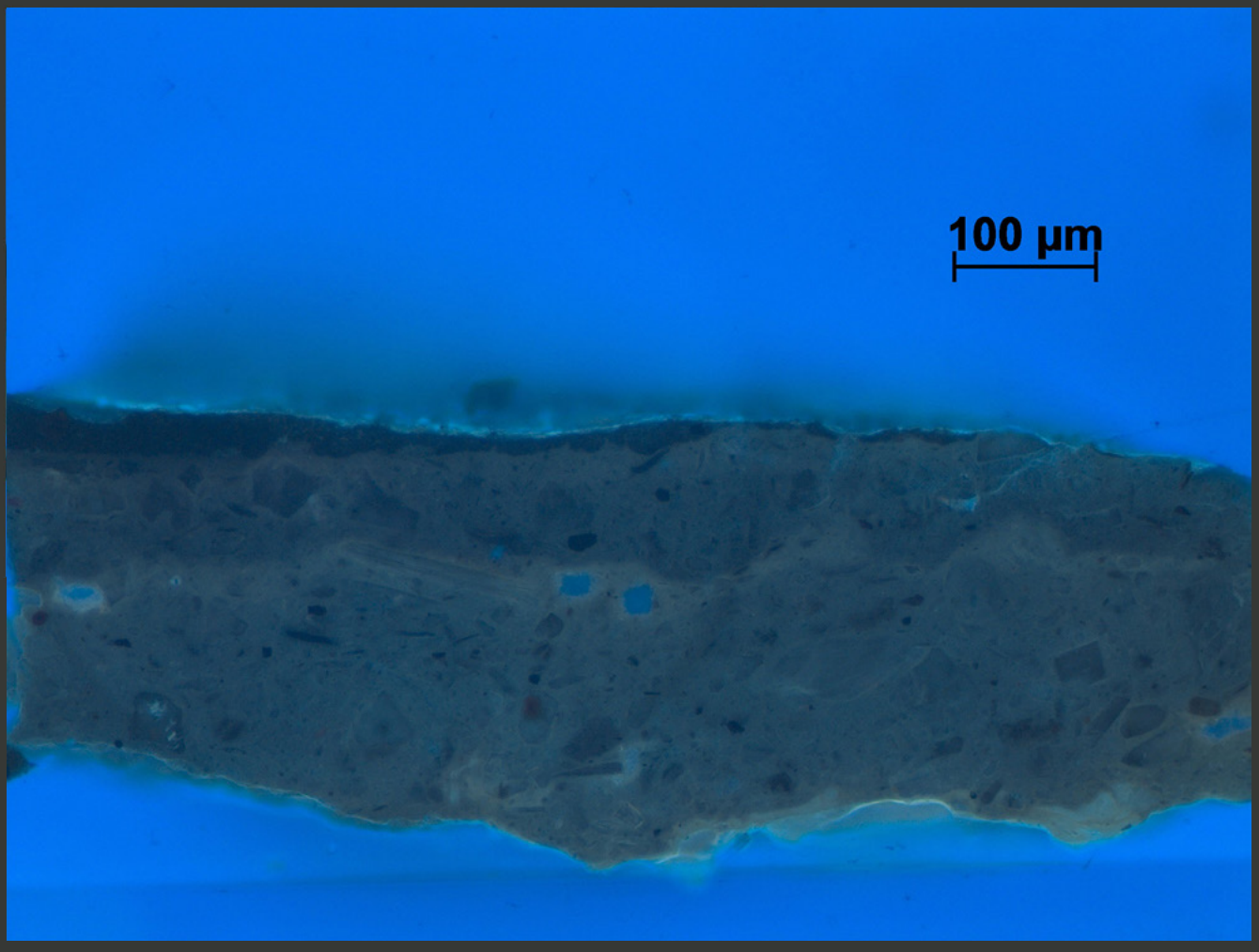
Caravaggio painted a fine black line along the top of Saint Andrew's bicep muscle. The line, which is rather sporadic, thin, and fluid, is quite prominent in the infrared images.

CROSS SECTIONS CS05

Normal Light



Excitation: UV (325-375 nm)
Emission: blue (λ_{em} > 420 nm)

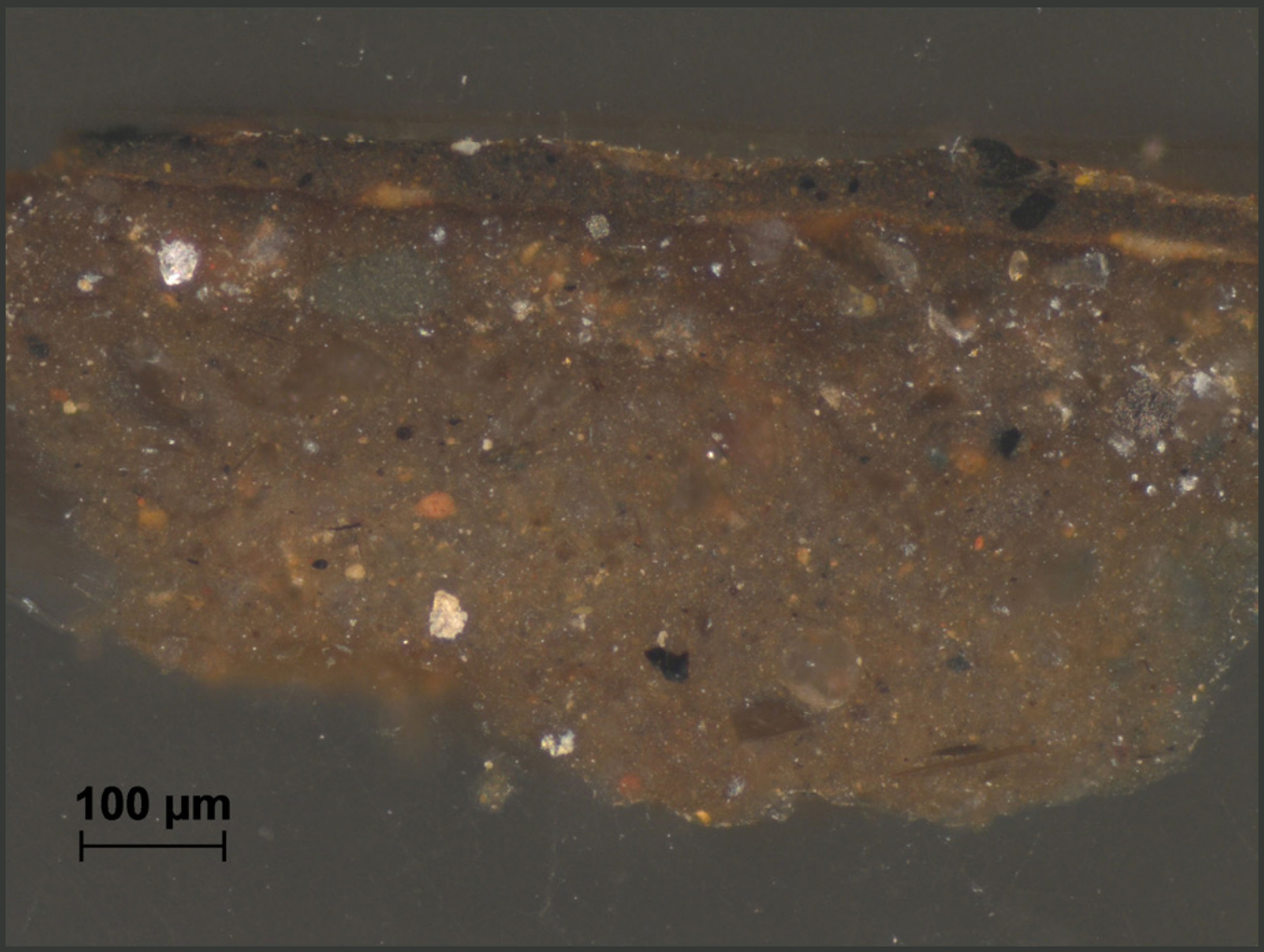


Cross Section 5 & 6 (CS05 & CS06)

Location: Saint Andrew's right bicep muscle

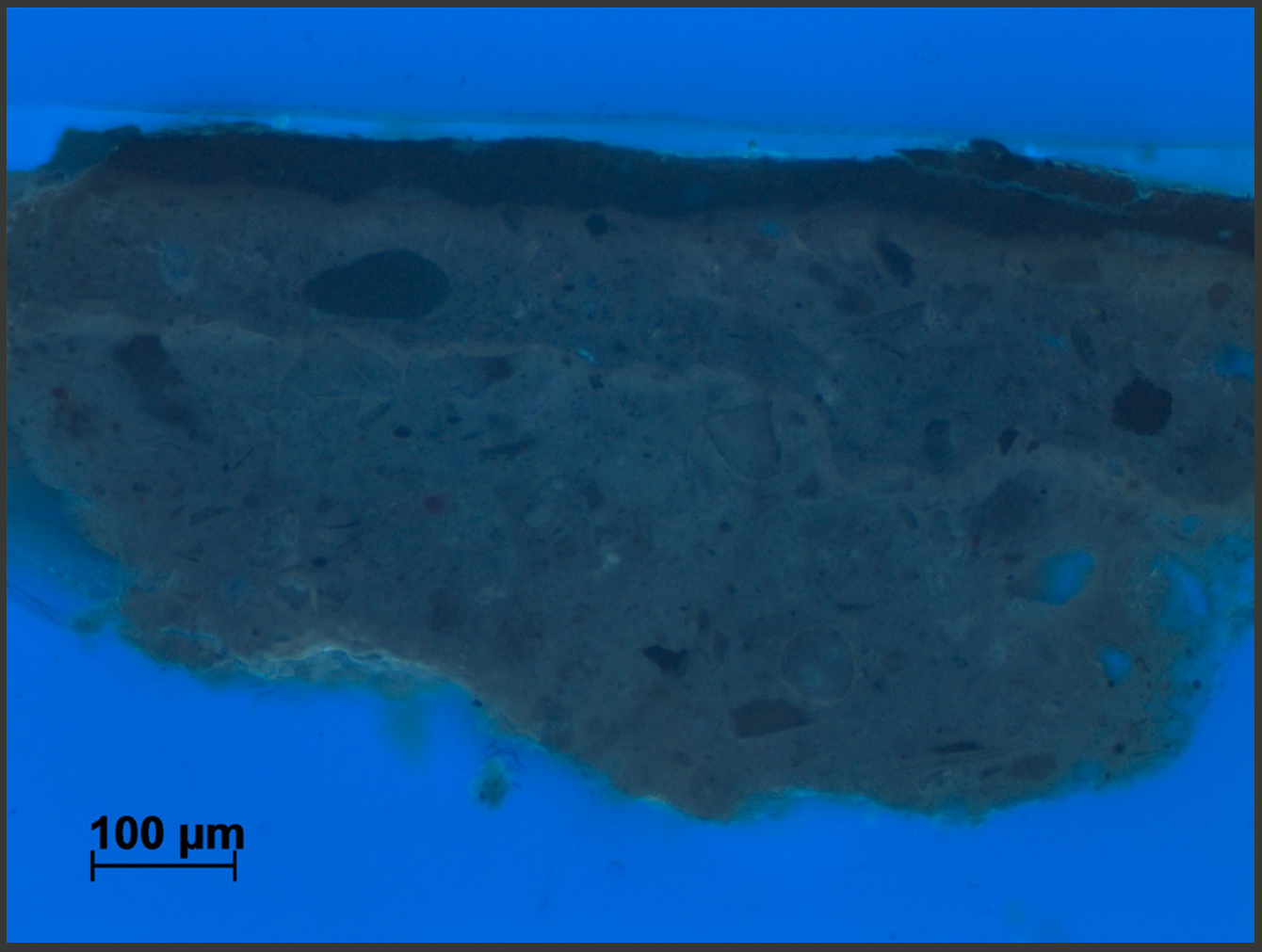
CROSS SECTIONS CS06

Normal Light



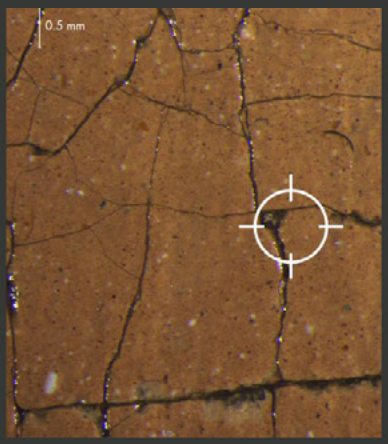
Cross sections 5 and 6 were taken from a painted line along the top of Saint Andrew's bicep muscle after removal of the varnish layers. As expected, the ground layers are similar to the other cross sections in structure and composition, showing a wide range of particles. The rationale behind taking cross sections 5 and 6 was to search for any unusual layers below the painted line. In normal light, cross section 6 exhibits a thin, sporadic, light-colored line just above the upper ground layer similar to that seen in cross section 2. Both normal light and UV images of cross sections 5 and 6 were taken at the IMA. [5] SEM-EDS has not yet been conducted on these samples. While it is premature to interpret this faint light layer as calcium based, future analysis could help determine whether it is chalk or gypsum and what purpose it might have served.

Excitation: UV (325-375 nm)
Emission: blue (λ_{em} > 412 nm)



Cross Section 7 (CS07)

Location: Highlight on Saint Andrew's pectoral muscle



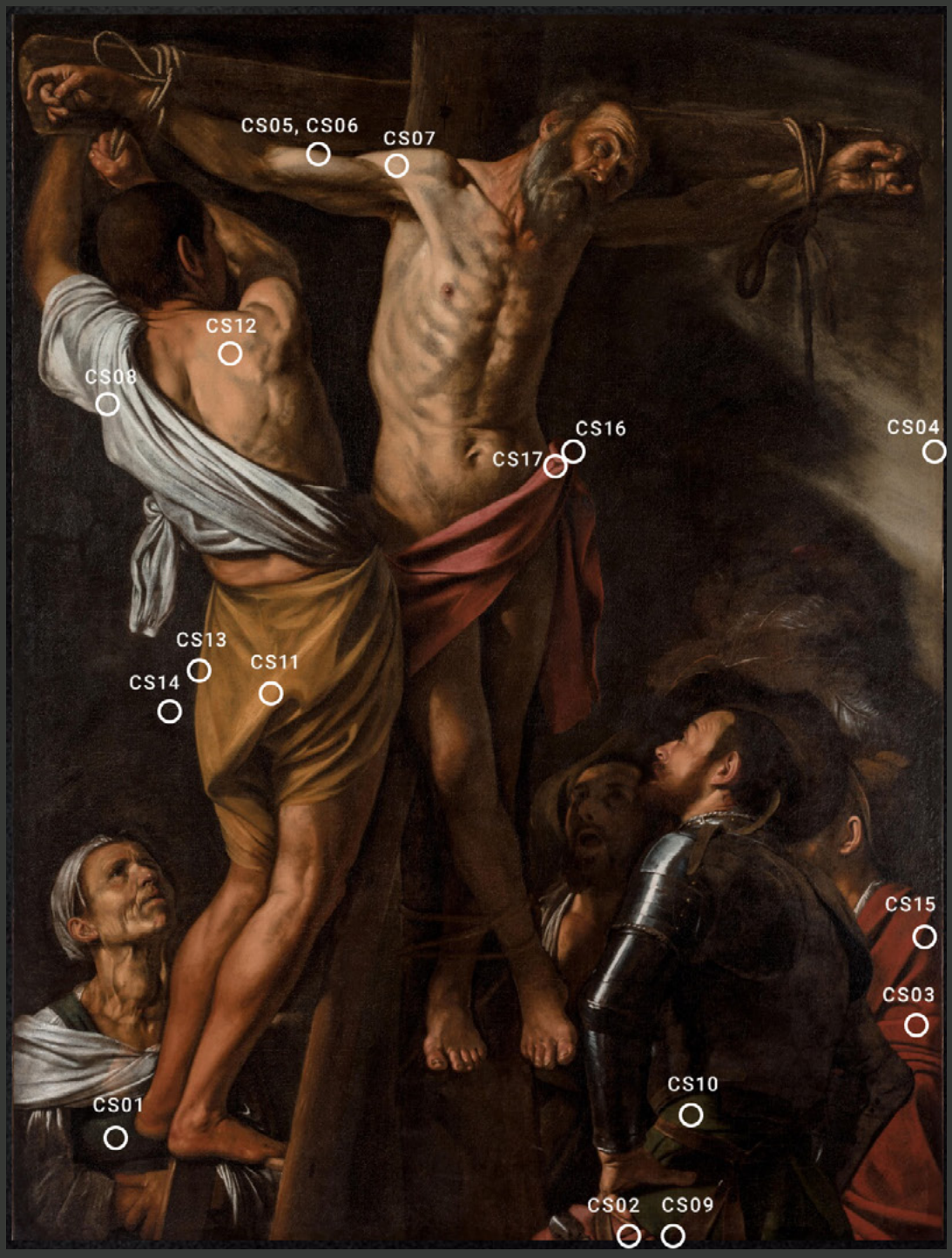
CROSS SECTIONS

GROUND LAYERS

RAMAN SPECTROSCOPY

PAINT LAYERS

SEM-EDS MAPS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

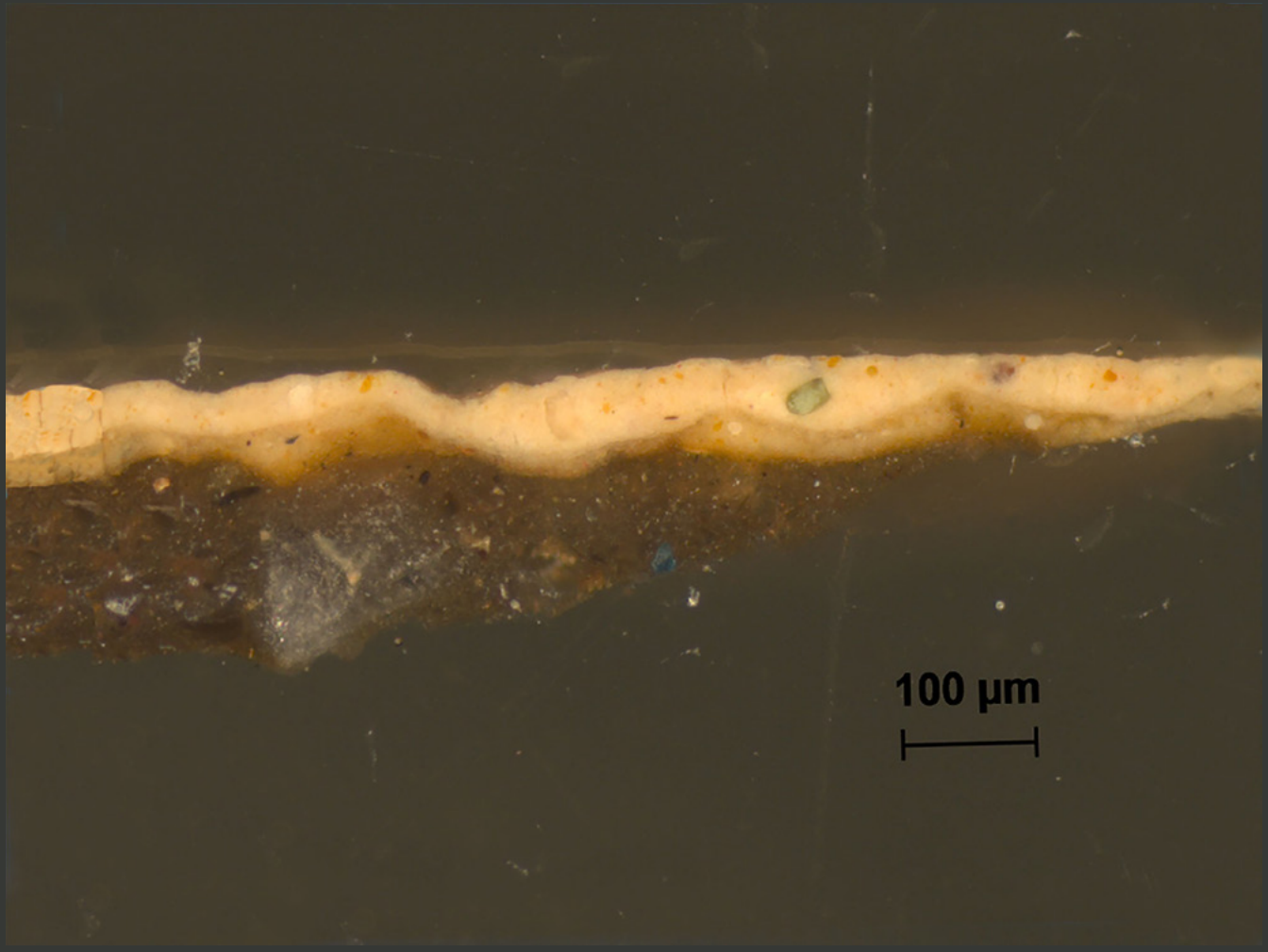
Cross Section 7 (CS07)

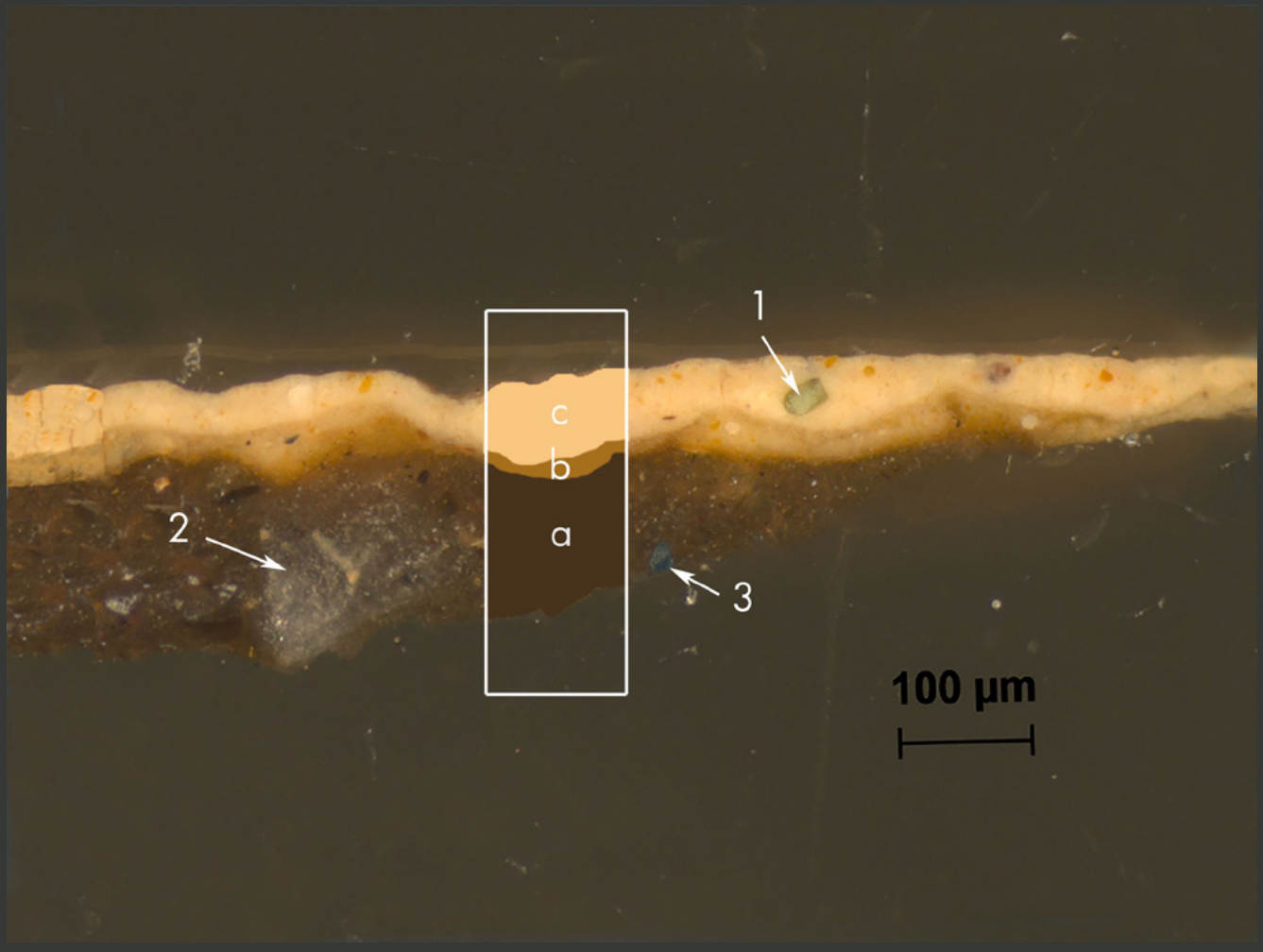
Location: Highlight on Saint Andrew's pectoral muscle

This sample was taken after cleaning to confirm the pigments used to create the skin tones of Saint Andrew.

CROSS SECTIONS

Normal Light Overlay



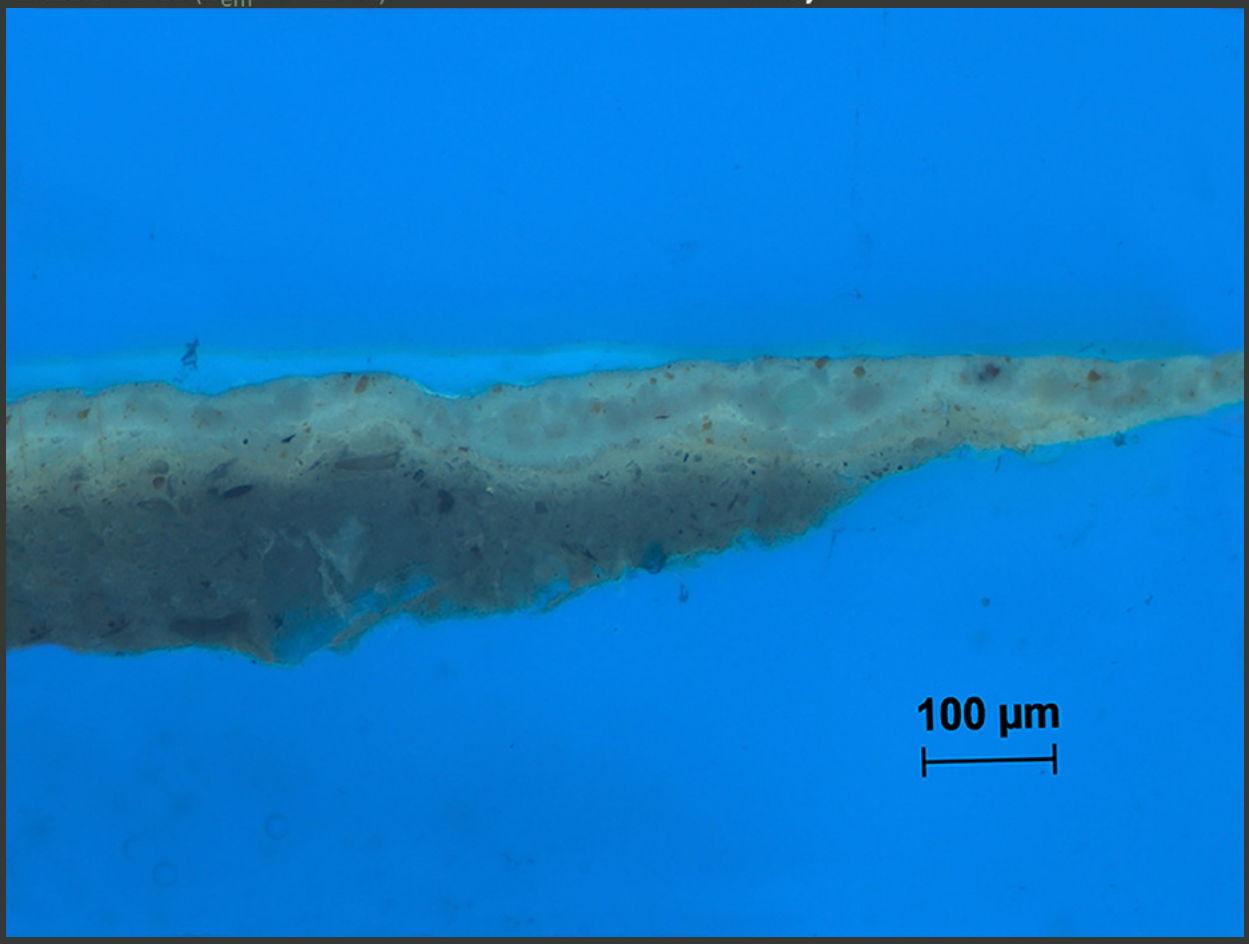

1
c
b
a
2
3
100 µm

Cross Section 7 (CS07)

Location: Highlight on Saint Andrew's pectoral muscle

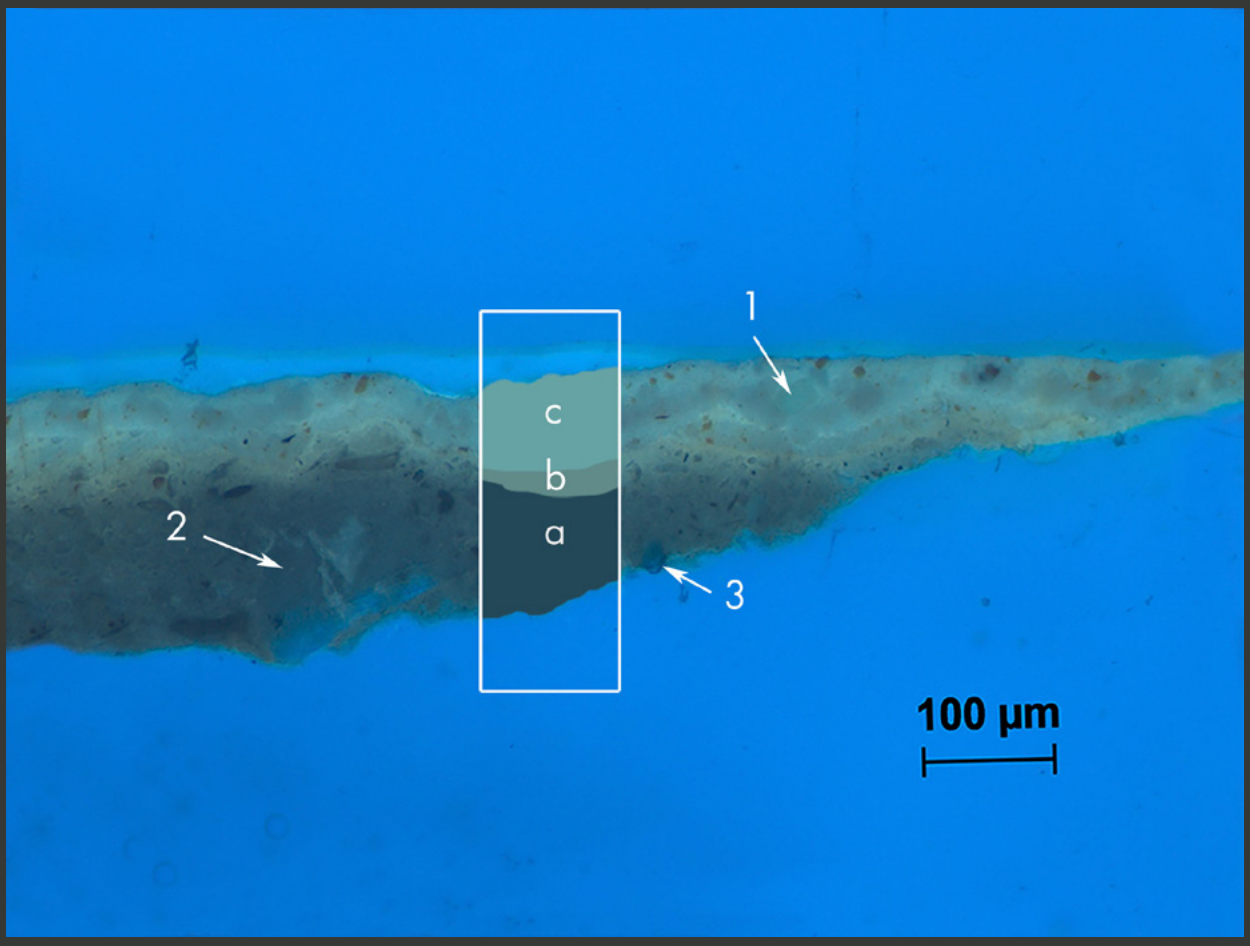
Excitation: UV (325-375 nm)
Emission: blue (λ_{em} > 412 nm)

Overlay



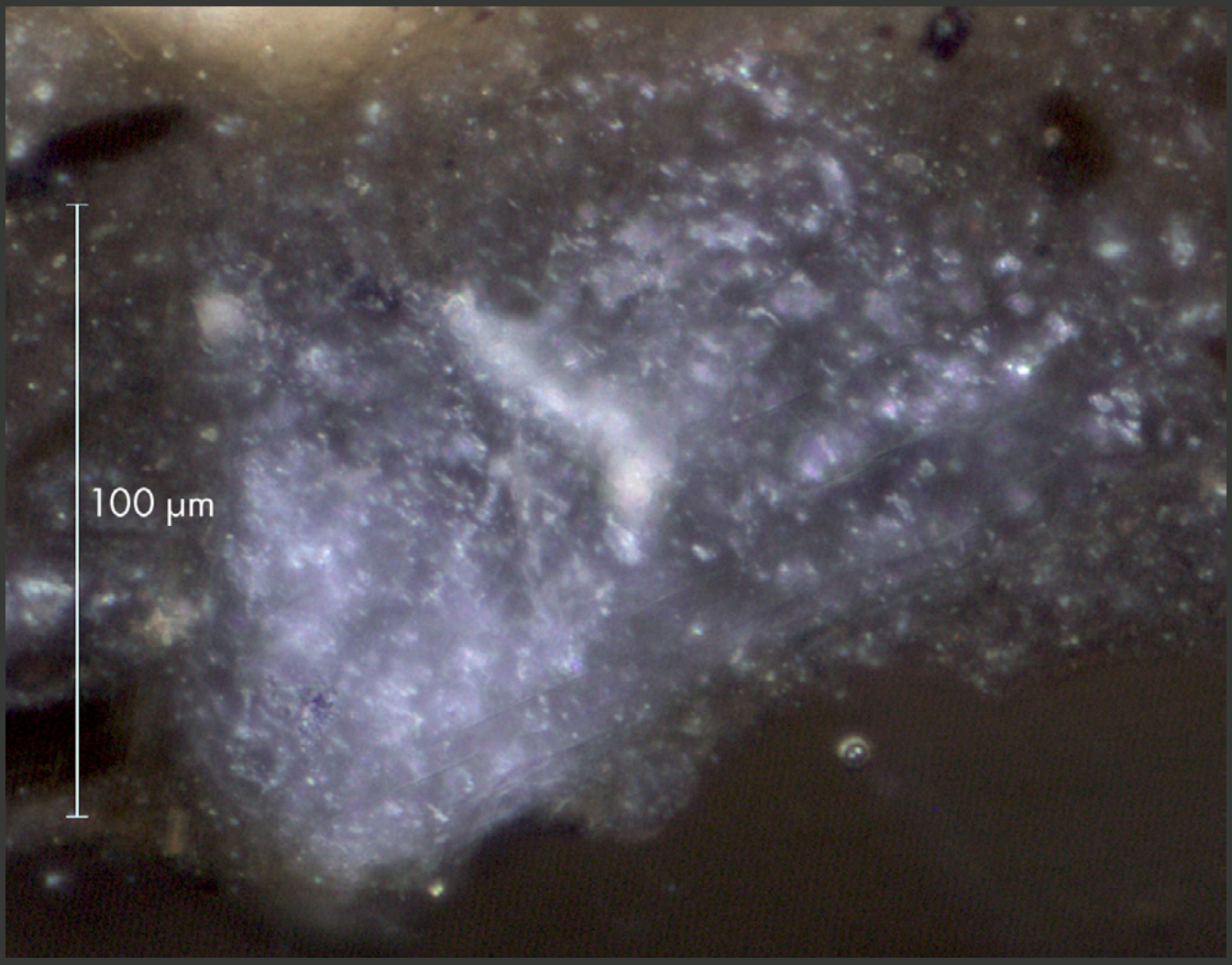
GROUND LAYERS

During the sample extraction process the lower ground remained attached to the canvas, while the upper ground remained adhered to the paint layers. SEM-EDS elemental maps show an even distribution of aluminosilicates and an even and wide distribution of iron in the upper ground layer (a). A large particle (2) composed of sodium, aluminum, silicon, and oxygen was identified by Raman spectroscopy as tectosilicate albite ($NaAlSi_3O_8$). A small copper-containing particle (3), confirmed by Raman analysis as azurite, corresponds to a blue particle and is present in the upper ground layer (a).

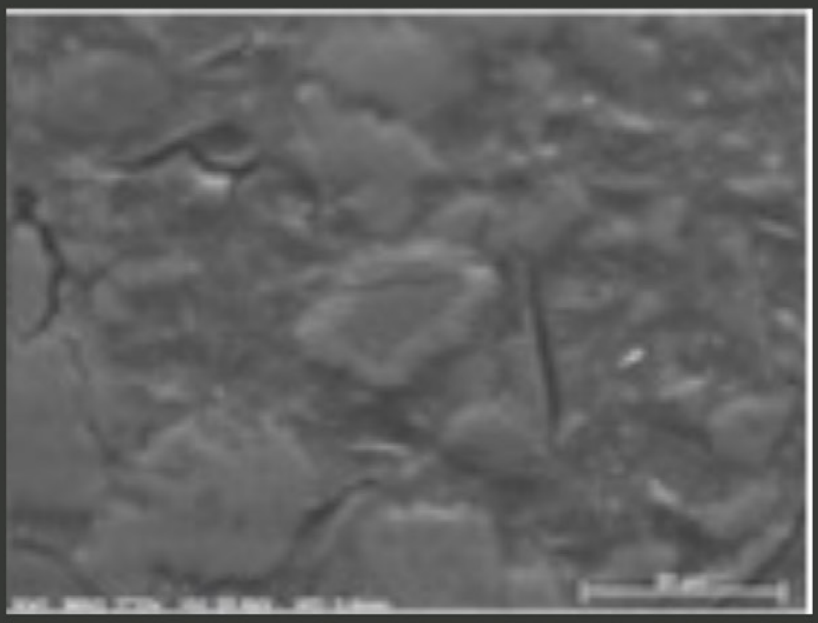

1
2
3
c
b
a
100 µm

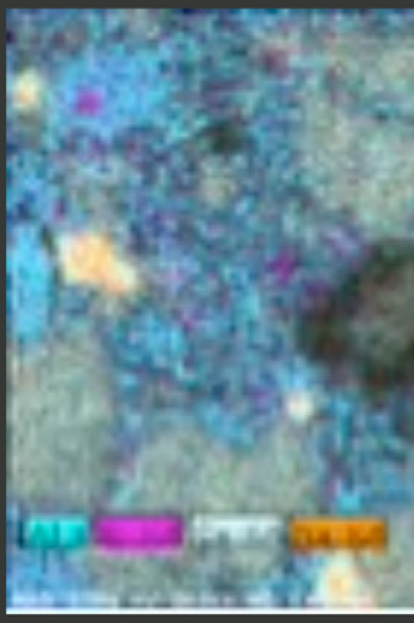
Cross Section 7 (CS07)

Location: Highlight on Saint Andrew's pectoral muscle

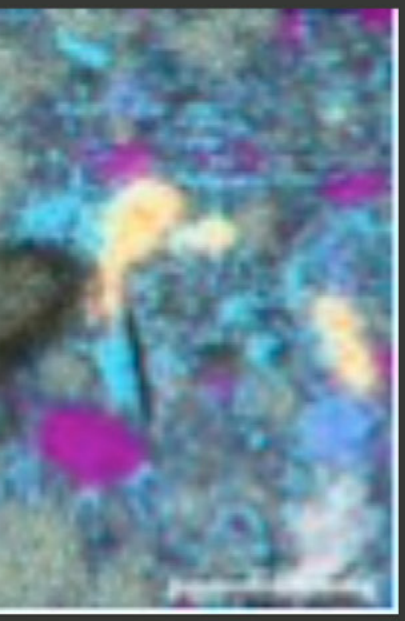


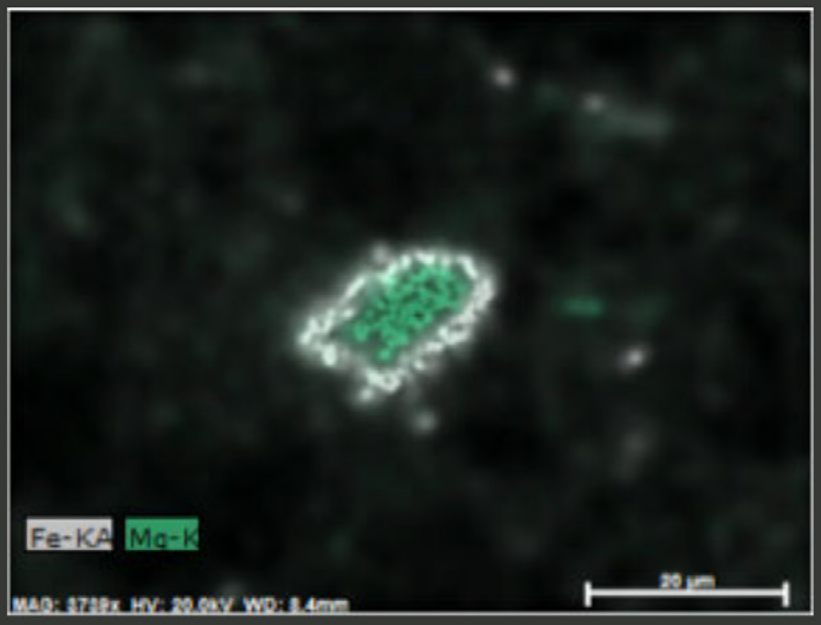
A detailed view (under normal light) of the clear translucent albite particle (sodium aluminum silicate) photographed at 200x.





An unusual particle with a magnesium and calcium center is surrounded by a ring consisting of iron oxide contained in a matrix bearing aluminum, silicon, calcium, and sodium-rich clays.

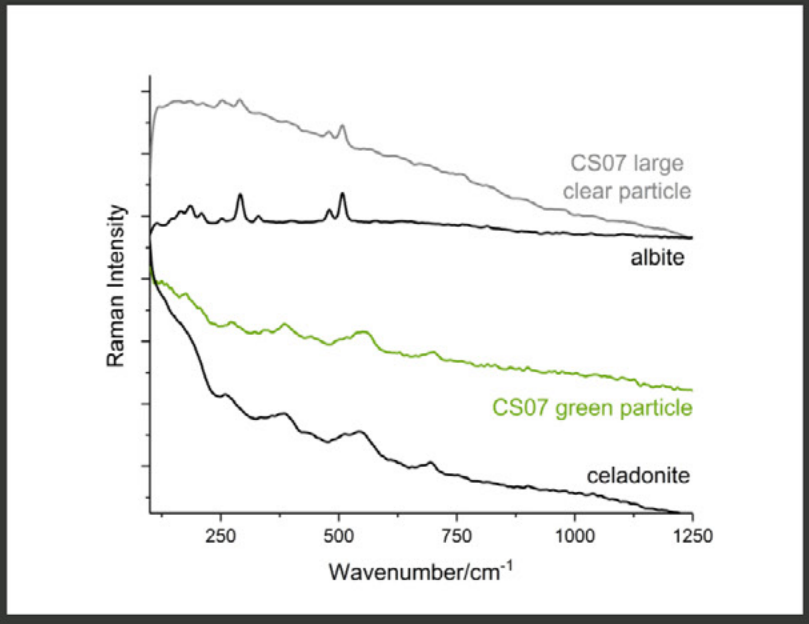



Fe-KA
Mg-K
20 µm

Cross Section 7 (CS07)

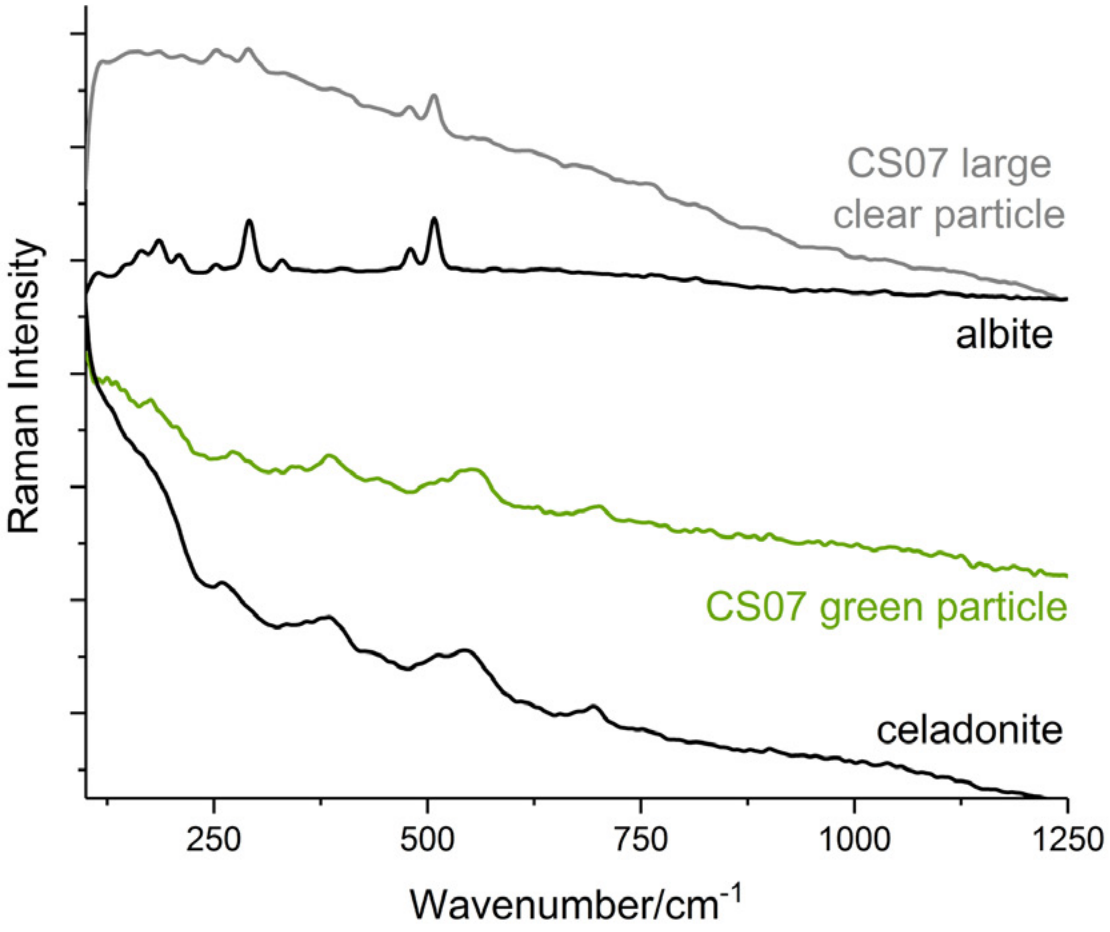
Location: Highlight on Saint Andrew's pectoral muscle

RAMAN SPECTROSCOPY



PAINT LAYERS

Two paint layers containing lead white pigment (b and c) can be seen in normal light. The lower layer (b) appears to contain less lead white according to the EDS map below. Yellow particles that correspond to elemental mapping of iron were confirmed as yellow ochre (FeOOH + silicates) by Raman spectroscopy. A similar distribution of sulfur to that of lead is also present in the top two paint layers; however, this strong indication of sulfur may also be due to the peak overlap interference between lead (M_α at 2.342 kiloelectron volts [keV]) and sulfur (K_α at 2.307 keV), despite attempting a spectral deconvolution of the two. [6] Because lake pigments have been found in Caravaggio's flesh tones, the presence of red lake in layers (b) and (c) might have been anticipated in this cross section. However, the EDS maps indicate the complete absence of both aluminum and


CS07 large
clear particle
albite
CS07 green particle
celadonite
Raman Intensity
250
500
750
1000
1250
Wavenumber/cm-1

Cross Section 7 (CS07)

Location: Highlight on Saint Andrew's pectoral muscle

PAINT LAYERS

Two paint layers containing lead white pigment (b and c) can be seen in normal light. The lower layer (b) appears to contain less lead white according to the EDS map below. Yellow particles that correspond to elemental mapping of iron were confirmed as yellow ochre (FeOOH + silicates) by Raman spectroscopy. A similar distribution of sulfur to that of lead is also present in the top two paint layers; however, this strong indication of sulfur may also be due to the peak overlap interference between lead (M_α at 2.342 kiloelectron volts [keV]) and sulfur (K_α at 2.307 keV), despite attempting a spectral deconvolution of the two. [6] Because lake pigments have been found in Caravaggio's flesh tones, the presence of red lake in layers (b) and (c) might have been anticipated in this cross section. However, the EDS maps indicate the complete absence of both aluminum and potassium (K) from this paint layer, likely ruling out the possibility of a lake pigment in these paint layers.

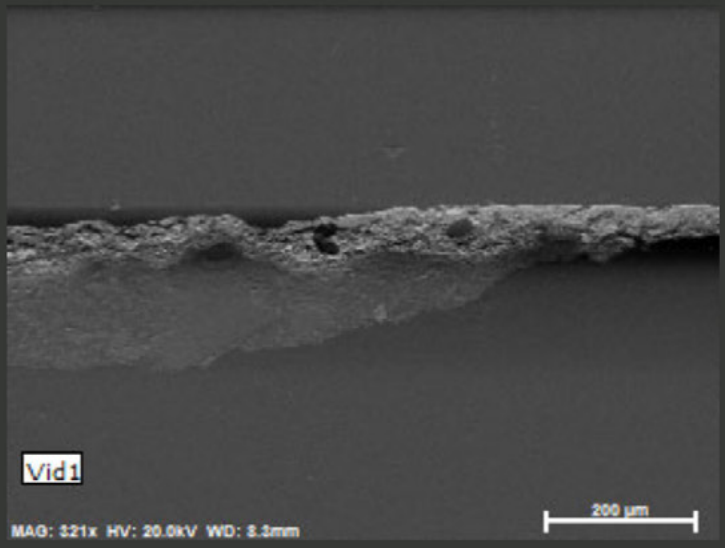
Scattered, translucent yellow particles directly correspond to the EDS maps for iron, indicating yellow ochre, and Raman spectroscopy confirmed a red particle in the upper paint layer as hematite. There is also a faint, diffuse distribution of copper in both paint layers, which does not appear to be associated with a particular particle. Similar diffuse distributions of copper, which cannot be linked to particular pigments, appear in other Caravaggio paintings, including flesh colors, but the cause is still not known. [7]

A large green particle (1) in the upper paint layer (c), is composed of potassium, iron, magnesium, silicon, traces of aluminum, and oxygen. This particle was later identified by Raman spectroscopy as a green earth, more specifically celadonite ($K(MgFe^{2+})(Fe^{3+},Al)[Si_4O_{10}](OH)_2$).

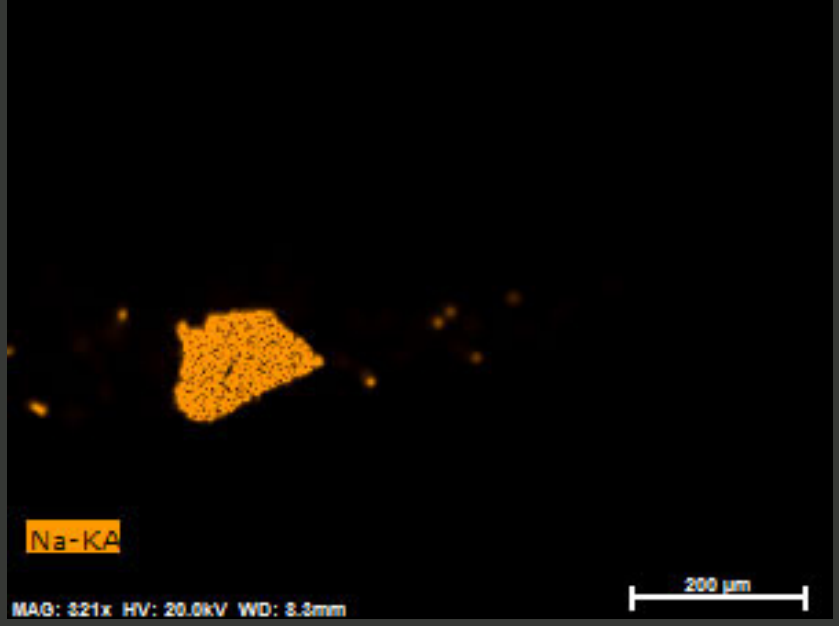
SEM-EDS MAPS

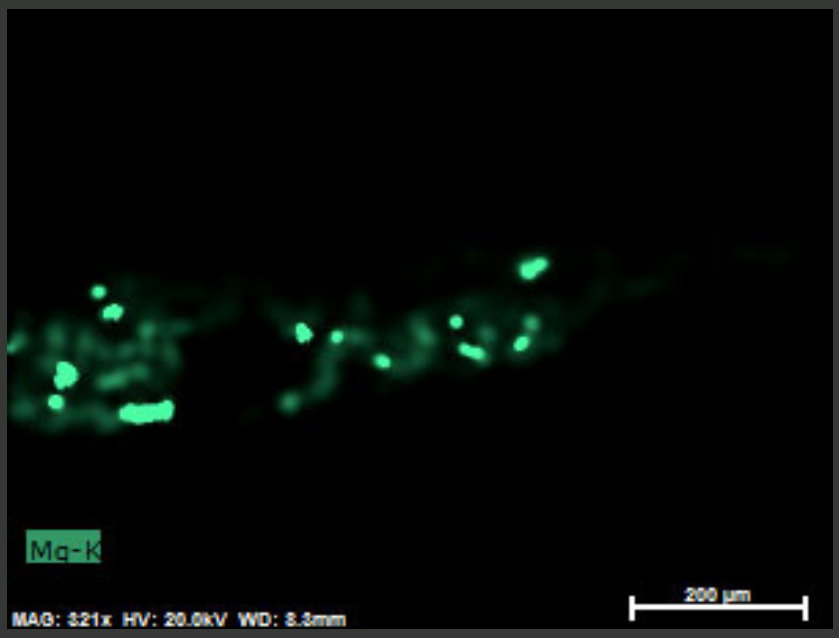
SEM-EDS MAPS

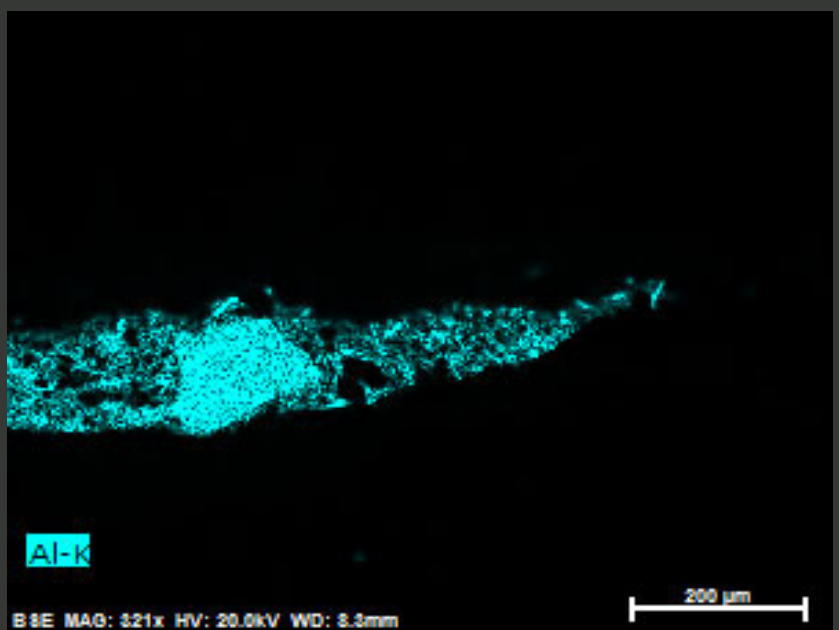
BSE
Na
Mg
Al
Si
P
S
K
Ca
Ti
Fe
Cu
Pb

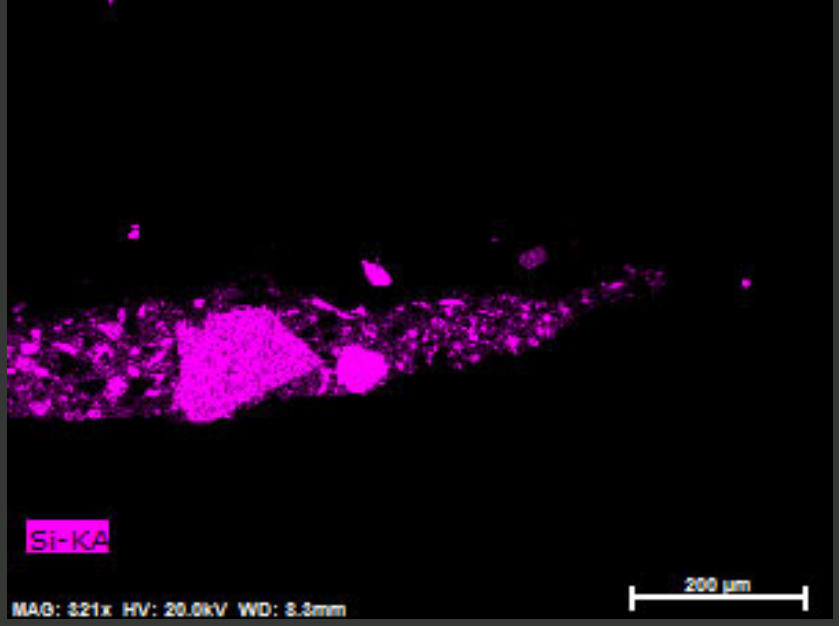


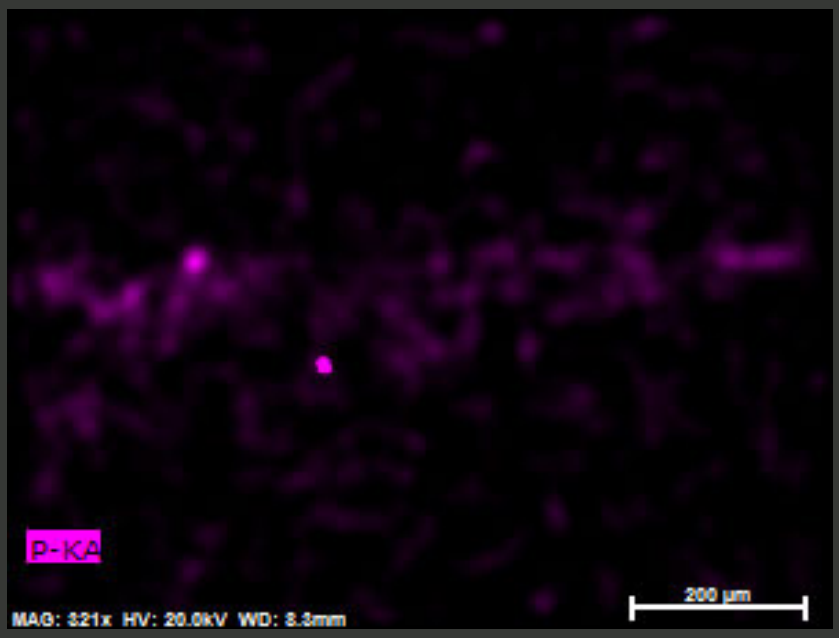
MAG: 321x
HV: 20 kV
WD: 8.3 mm
Scale bar: 200 µm

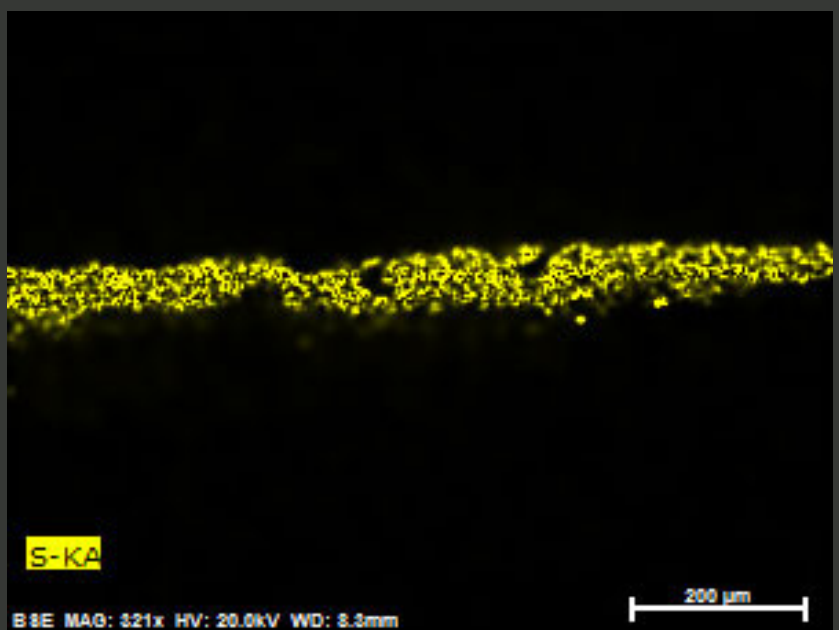

Na-KA
200 µm
MAG: 321x HV: 20.0kV WD: 8.3mm

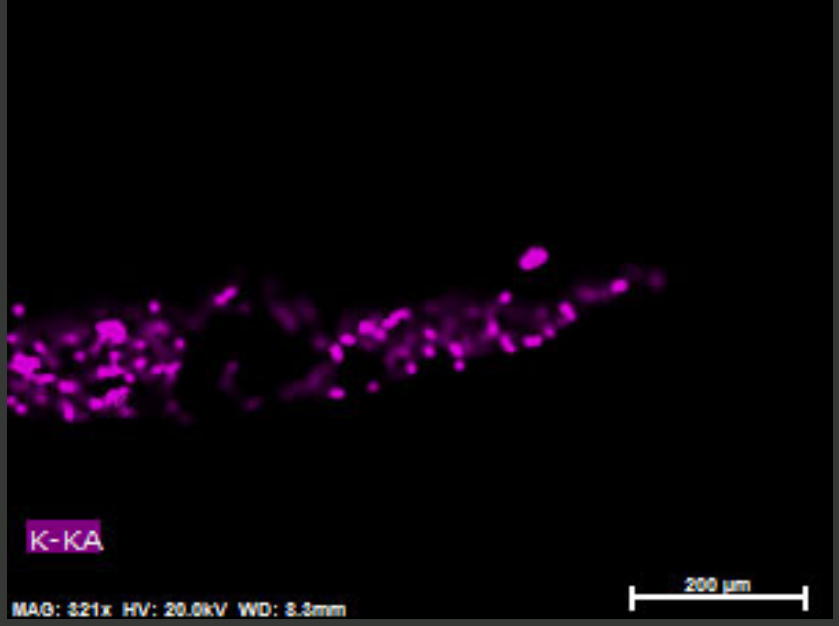

Mg-K
200 µm
MAG: 321x HV: 20.0kV WD: 8.3mm

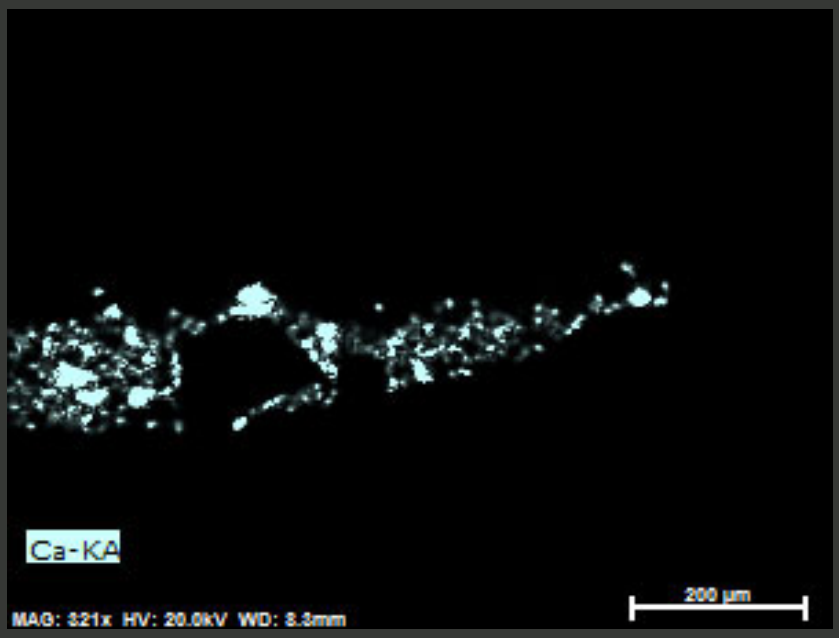

Al-K
200 µm
BSE MAG: 321x HV: 20.0kV WD: 8.3mm

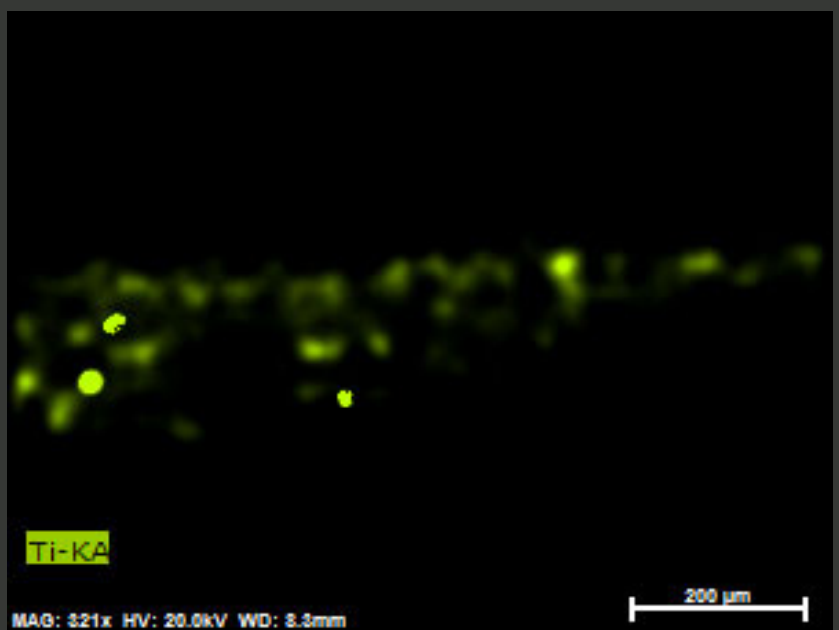

Si-KA
MAG: 321x HV: 20.0kV WD: 8.3mm
200 µm

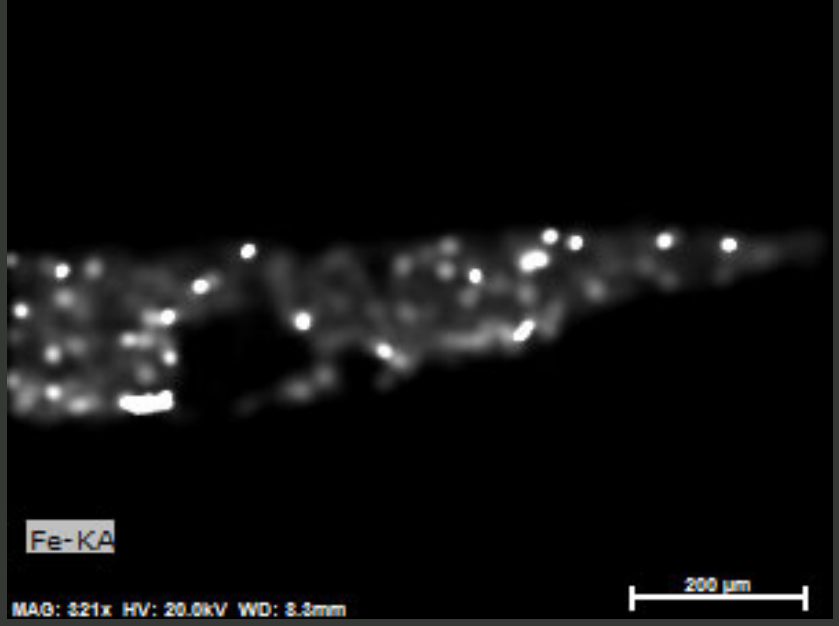

P-KA
MAG: 321x HV: 20.0kV WD: 8.3mm
200 µm

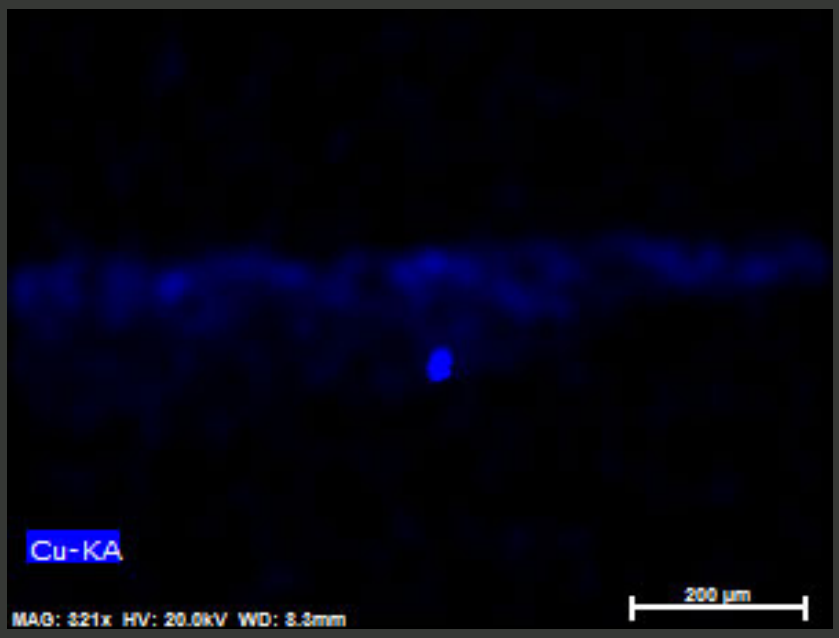

S-KA
B SE MAG: 321x HV: 20.0kV WD: 8.3mm
200 µm

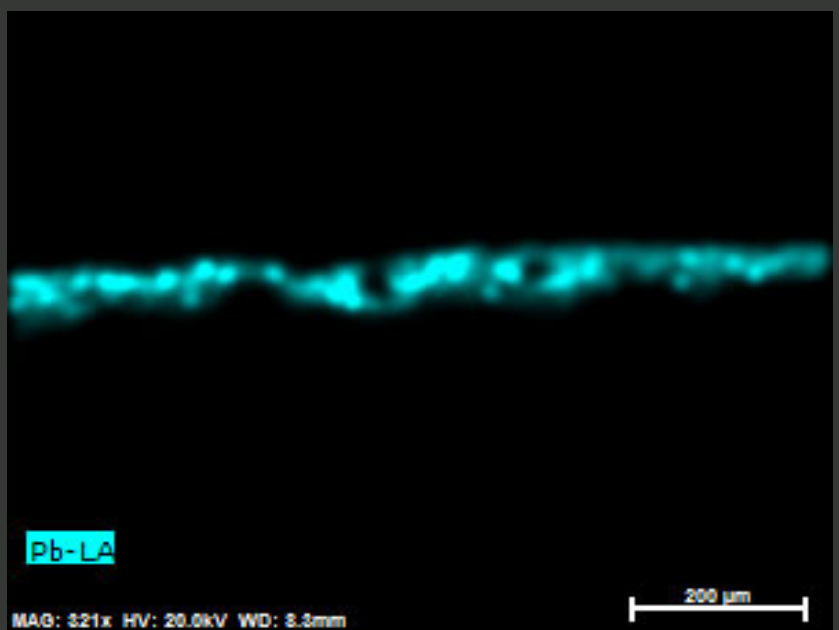

K-KA
MAG: 321x HV: 20.0kV WD: 8.3mm
200 µm


Ca-KA
MAG: 321x HV: 20.0kV WD: 8.3mm
200 µm


Ti-KA
MAG: 321x HV: 20.0kV WD: 8.3mm
200 µm


Fe-KA
MAG: 321x HV: 20.0kV WD: 8.3mm
200 µm

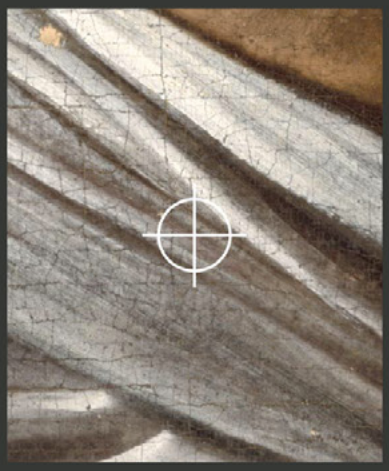

Cu-KA
MAG: 321x HV: 20.0kV WD: 8.3mm
200 µm


Pb-LA
MAG: 321x HV: 20.0kV WD: 8.3mm
200 µm

Cross Section 8 (CS08)

Location: White highlight of the standing figure from an incision area

This sample was taken after cleaning to identify the pigments used to create the white drapery and to search for any underlying pigments below the incision.



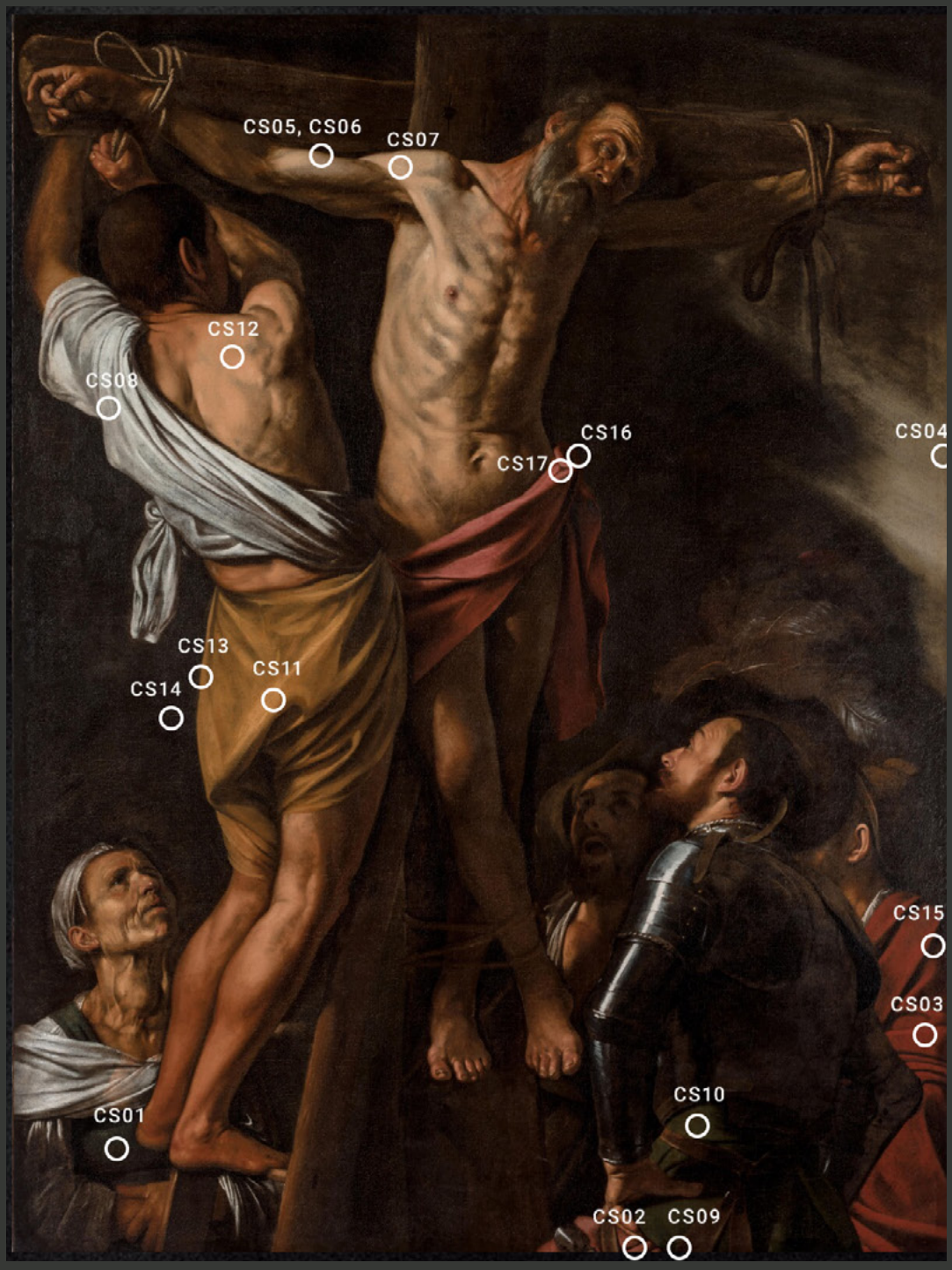
CROSS SECTIONS

GROUND LAYERS

SEM-BSE IMAGES

PAINT LAYERS

SEM-EDS MAPS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

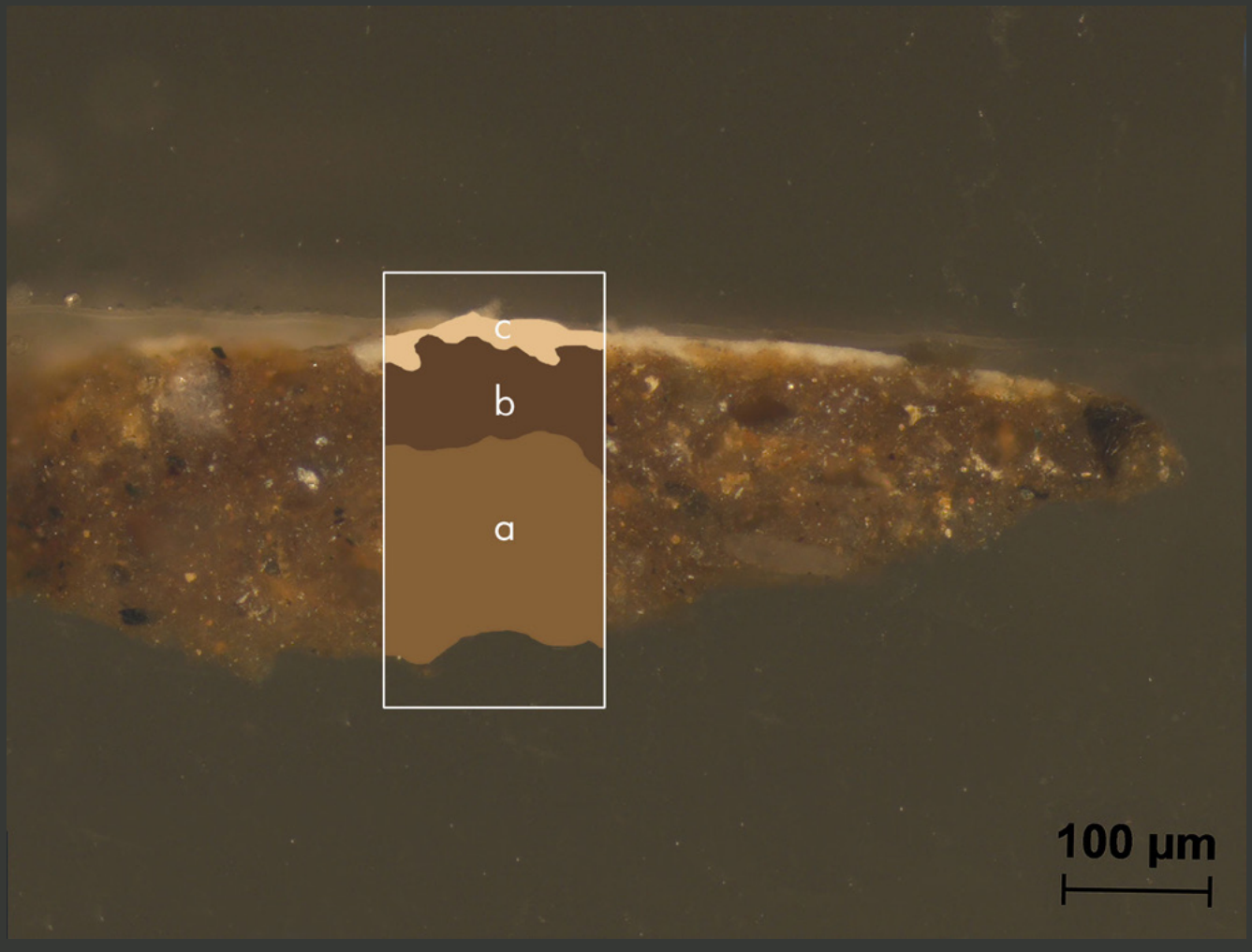
Cross Section 8 (CS08)

Location: White highlight of the standing figure from an incision area

This sample was taken after cleaning to identify the pigments used to create the white drapery and to search for any underlying pigments below the incision.

CROSS SECTIONS

Normal Light Overlay

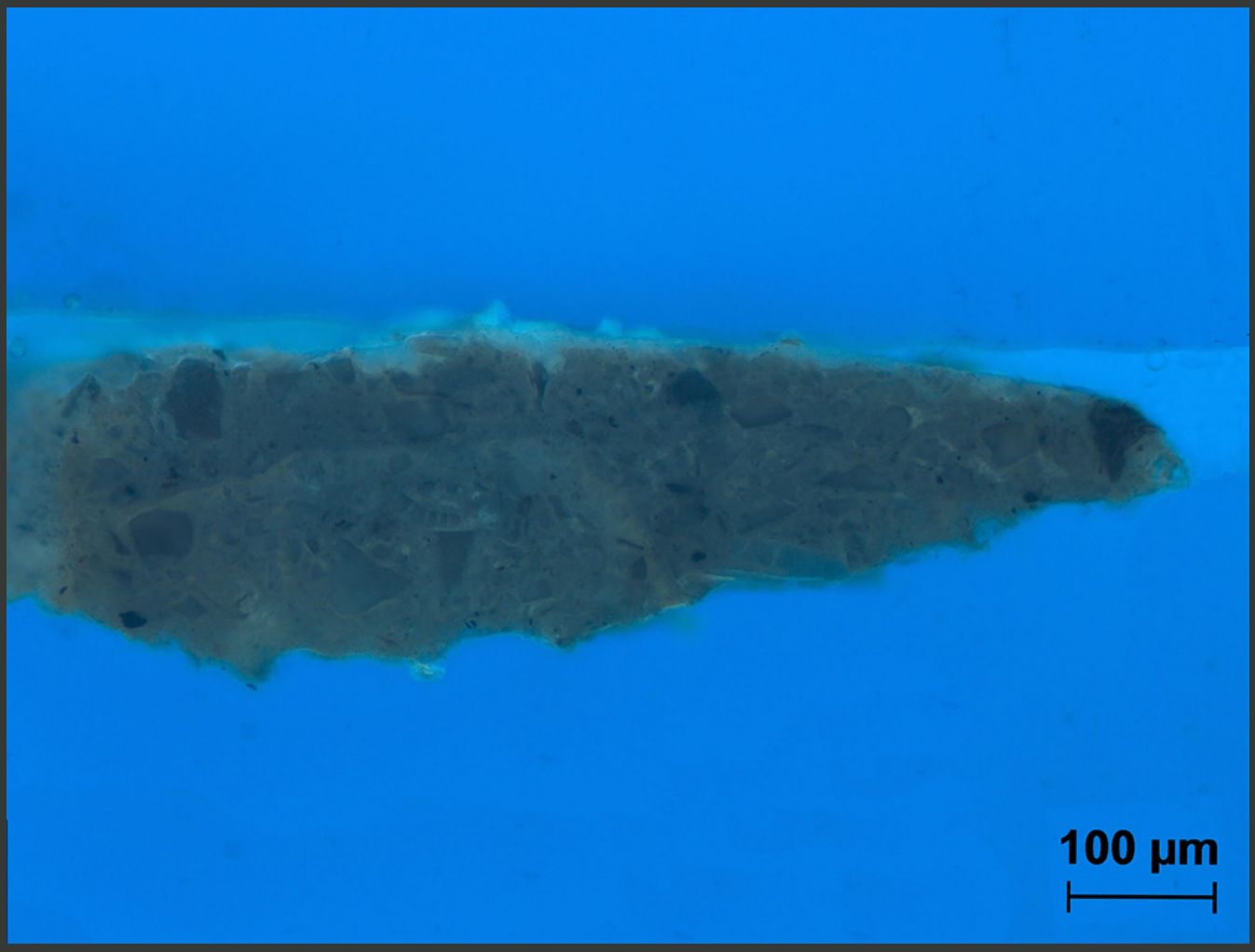

c
b
a
100 µm

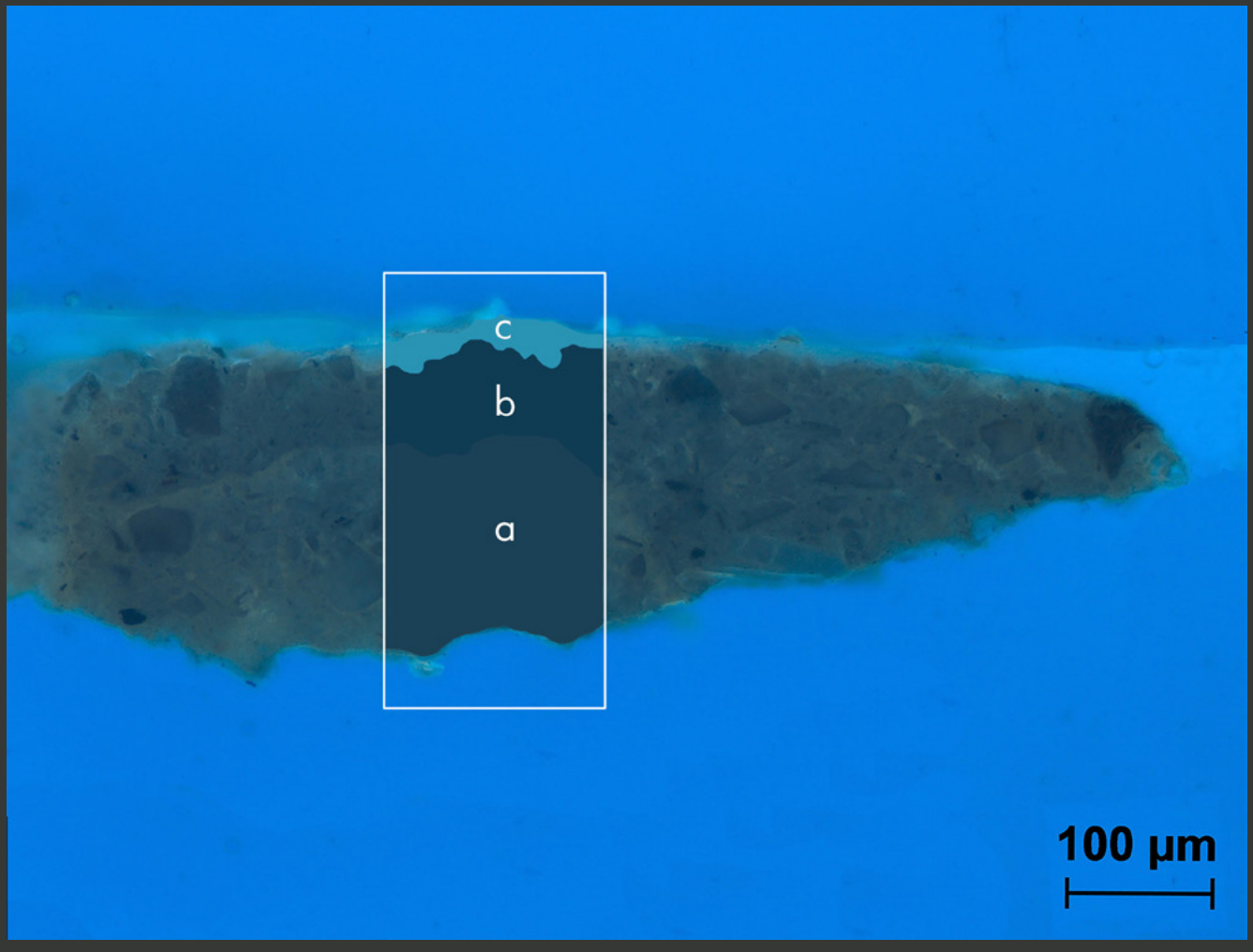
Cross Section 8 (CS08)

Location: White highlight of the standing figure from an incision area

Excitation: UV (325-375 nm)
Emission: blue (λ_{em} > 412 nm)

Overlay




c
b
a
100 µm

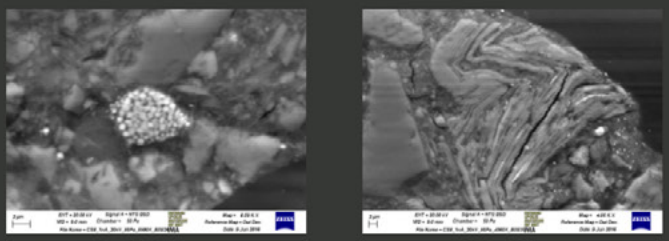
Cross Section 8 (CS08)

Location: White highlight of the standing figure from an incision area

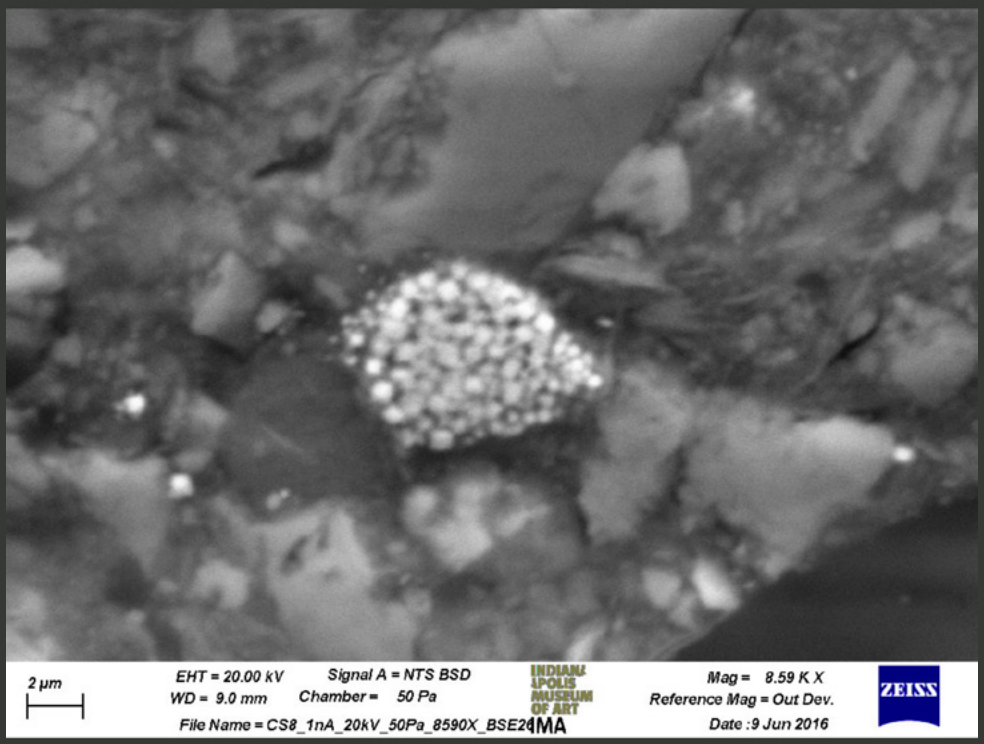
GROUND LAYERS

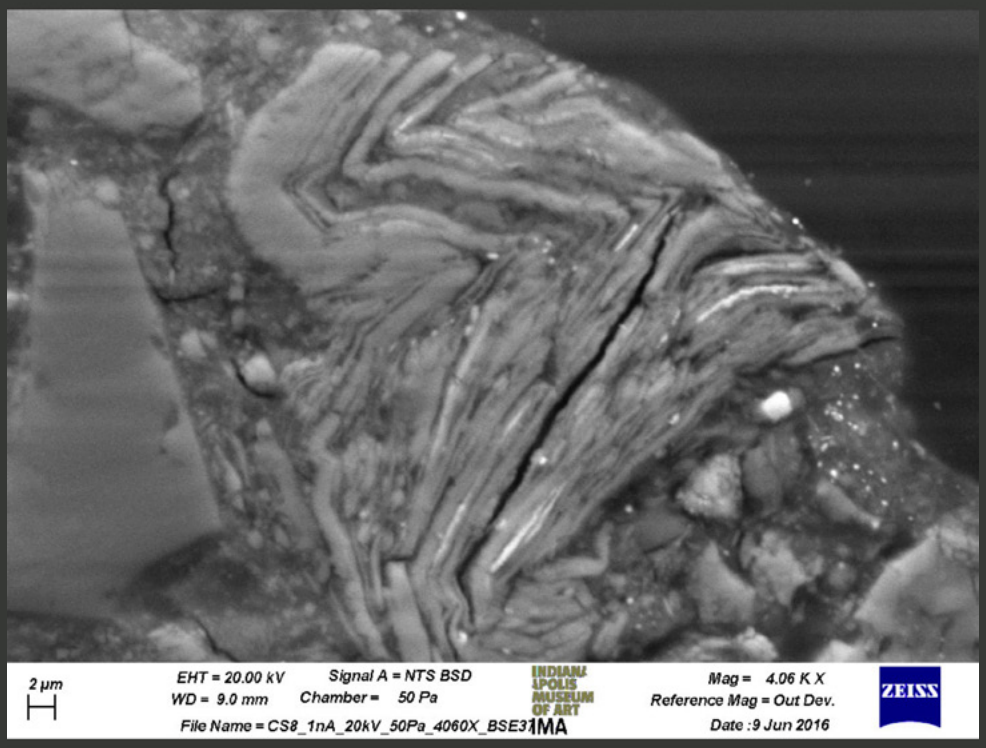
The SEM-EDS maps indicate an even distribution of aluminosilicates, calcium, potassium, and sodium in both upper and lower ground layers. The upper ground contains two large concentrated particles bearing iron; two fairly intense spots of copper, possibly azurite; and a large particle containing phosphorus, indicating the presence of bone black. Two smaller indications of phosphorus-rich particles are present in the lower ground. SEM images using backscattered electrons reveal unusual particle morphologies throughout the ground layers. Small framboids of pyrite and unidentified layered and folded aluminosilicate clay particles were visible at high magnification (8,590x).

BSE IMAGES



Ground layer of cross section 8: left, pyrite framboid; right, an unusual particle with folded layer structure magnified 8,590x with SEM.


2 µm
EHT = 20.00 kV
WD = 9.0 mm
Signal A = NTS BSD
Chamber = 50 Pa
File Name = CS8_1nA_20kV_50Pa_8590X_BSE2
Mag = 8.59 K X
Reference Mag = Out Dev.
Date :9 Jun 2016
ZEISS


2 µm
EHT = 20.00 kV
WD = 9.0 mm
Signal A = NTS BSD
Chamber = 50 Pa
File Name = CS8_1nA_20kV_50Pa_4060X_BSE3
Mag = 4.06 K X
Reference Mag = Out Dev.
Date :9 Jun 2016
ZEISS

Cross Section 8 (CS08)

Location: White highlight of the standing figure from an incision area

PAINT LAYERS

A thin layer of lead white paint is over the upper ground layer. A faint amount of copper and calcium appears to be present in the top lead white paint layer, as well as a strong sulfur signal. The last, however, may be due to peak overlap interference between lead (Mα at 2.342 kiloelectron volts [keV]) and sulfur (K_α at 2.307 keV), which nonetheless remained after running a deconvolution program. The analysis reveals no unusual layers or concentrations of elements below this area where an incision was cut into the upper ground.

SEM-EDS MAPS

BSE

Na

Mg

Al

Si

P

S

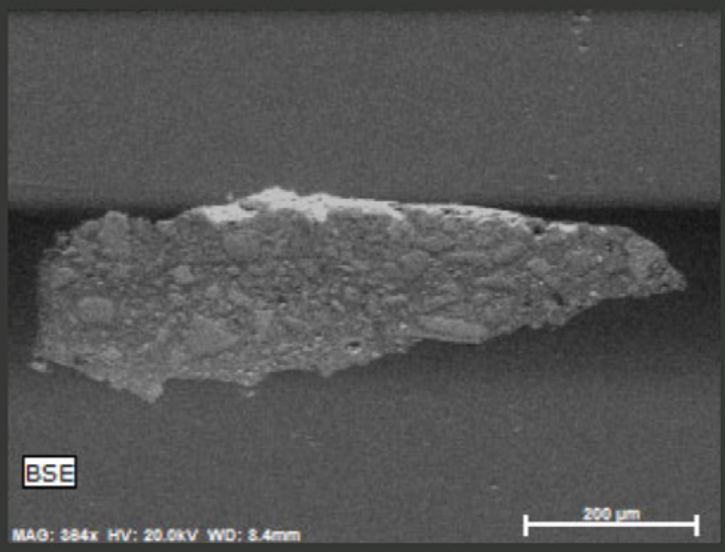
K

Ca

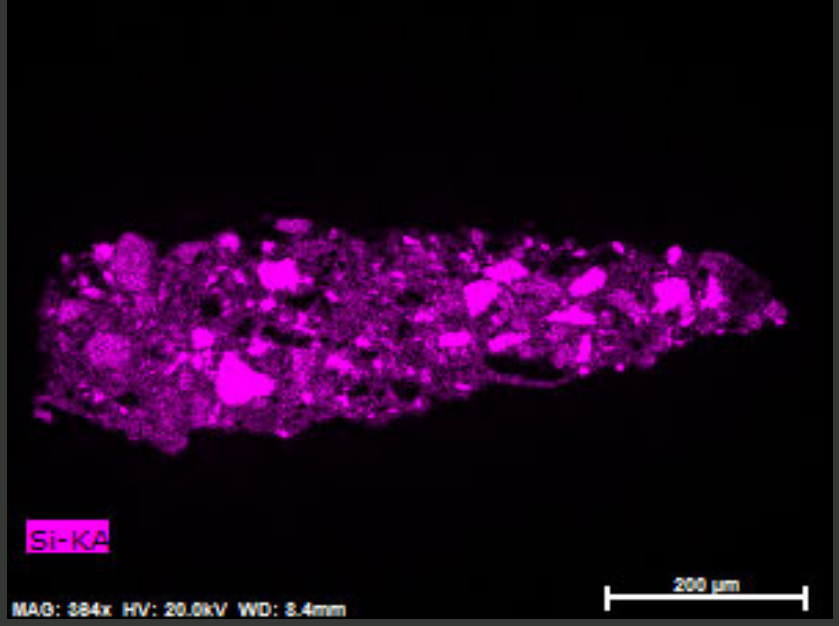
Fe

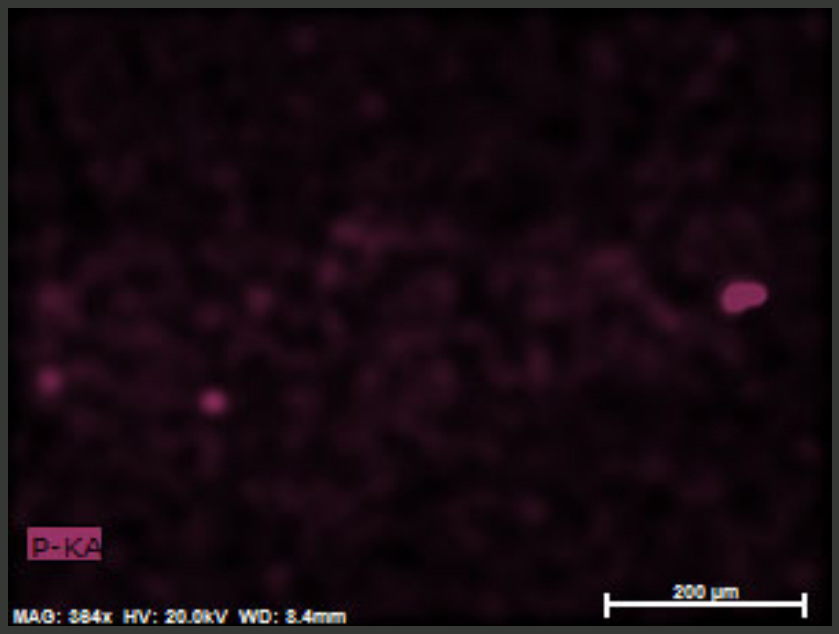
Cu

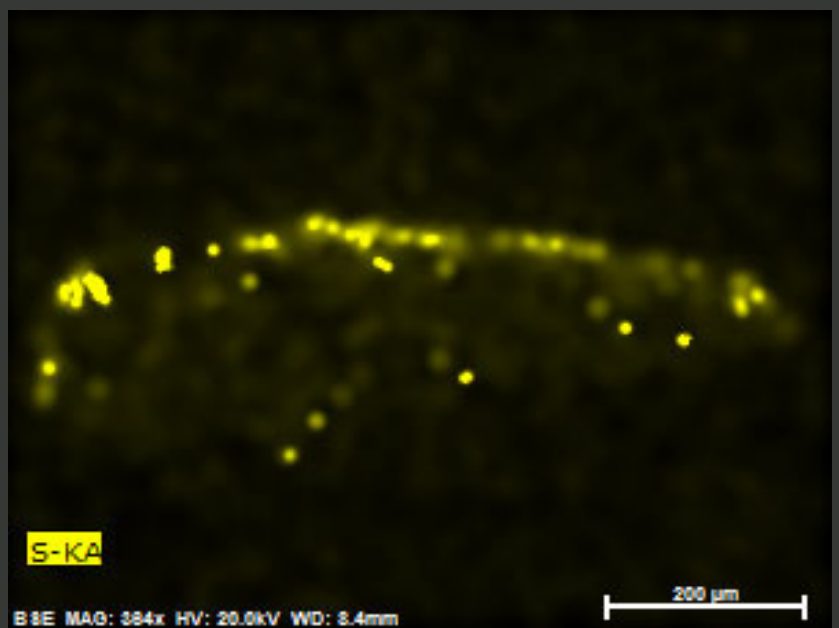
Pb



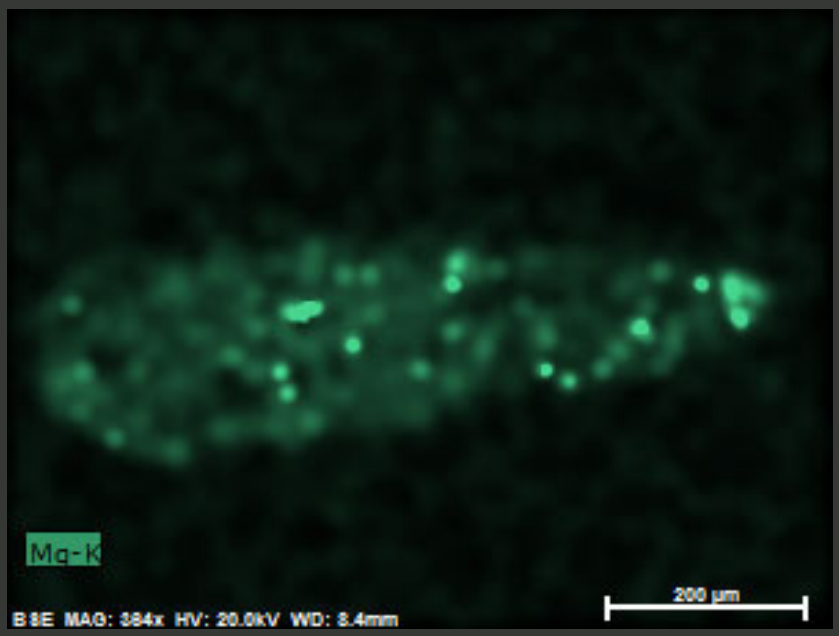
MAG: 384x
HV: 20 kV
WD: 8.4 mm
Scale bar: 200 µm

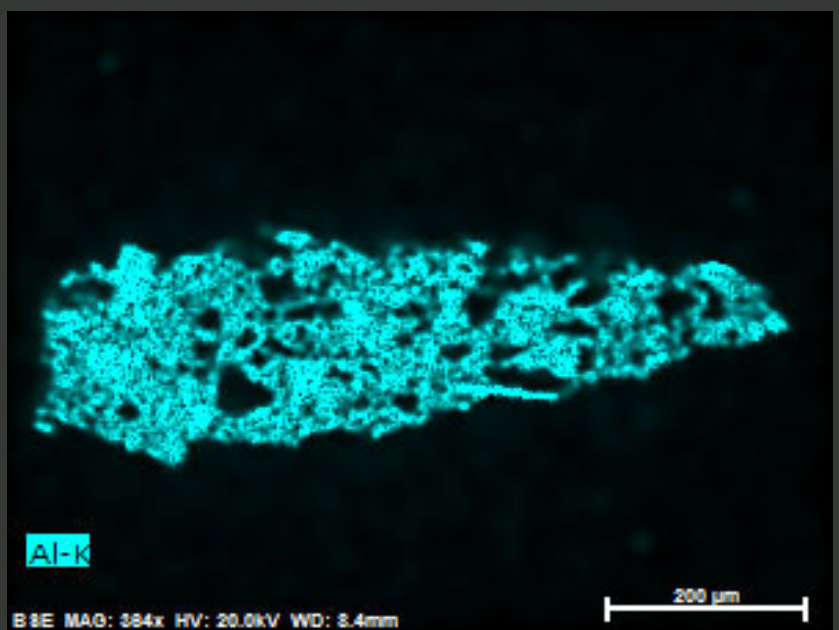

Si-KA
MAG: 384x HV: 20.0kV WD: 8.4mm
200 µm

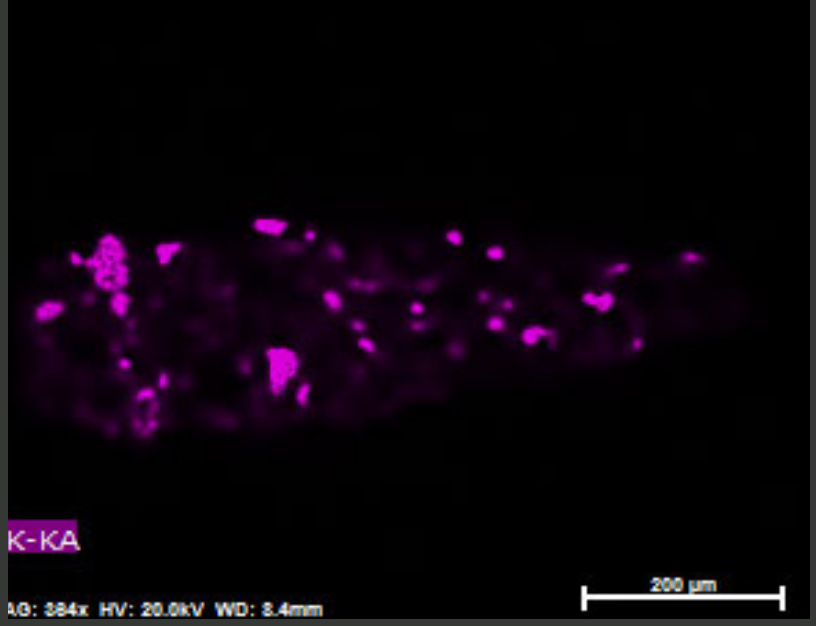

P-KA
MAG: 384x HV: 20.0kV WD: 8.4mm
200 µm

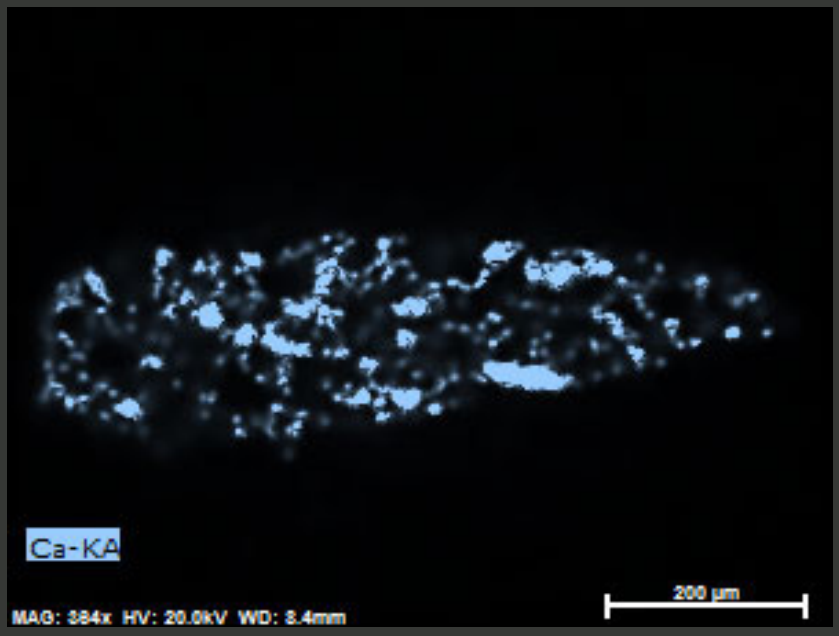

S-KA
B SE MAG: 384x HV: 20.0kV WD: 8.4mm
200 µm

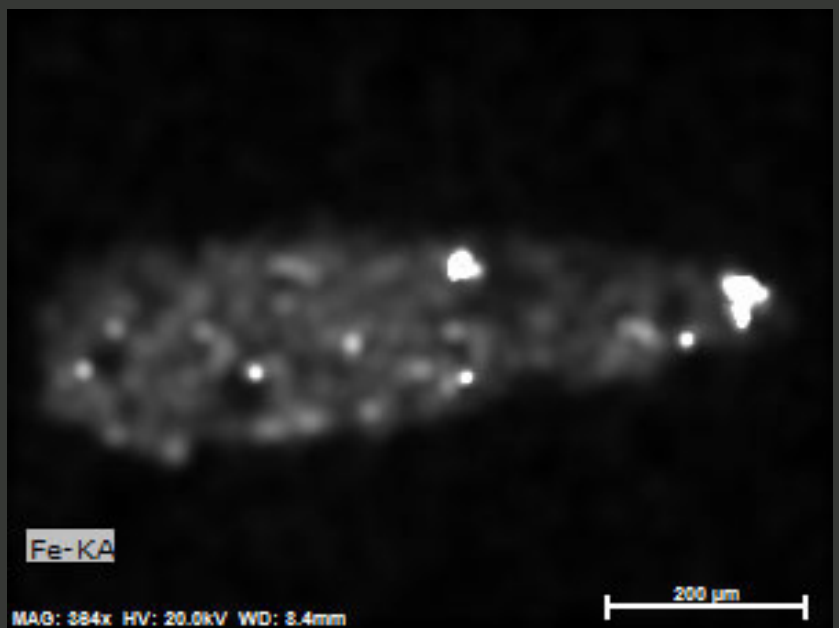
Na-KA
200 µm
MAG: 384x HV: 20.0kV WD: 8.4mm

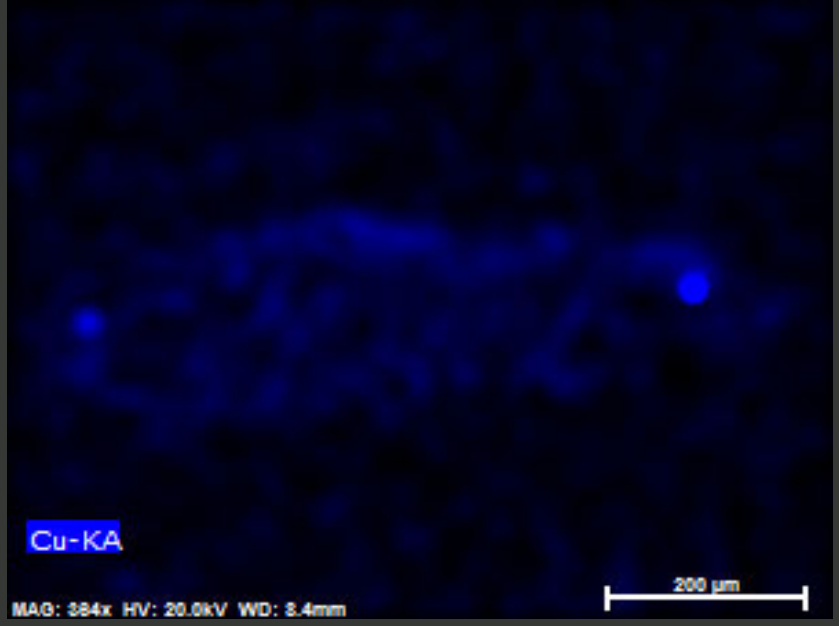

Mg-K
200 µm
BSE MAG: 384x HV: 20.0kV WD: 8.4mm


Al-K
200 µm
BSE MAG: 384x HV: 20.0kV WD: 8.4mm


K-KA
AG: 384x HV: 20.0kV WD: 8.4mm
200 µm


Ca-KA
MAG: 384x HV: 20.0kV WD: 8.4mm
200 µm


Fe-KA
MAG: 384x HV: 20.0kV WD: 8.4mm
200 µm

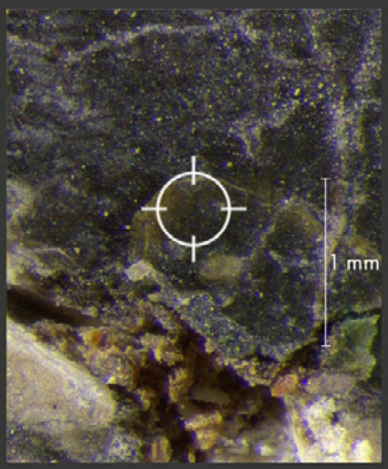

Cu-KA
200 µm
MAG: 384x HV: 20.0kV WD: 8.4mm

Pb-LA
200 µm
MAG: 384x HV: 20.0kV WD: 8.4mm

Cross Section 9 (CS09)

Location: Lower edge of the soldier's garment, after cleaning

This sample was taken to identify the pigments and paint structure used to create the green waistcoat.



CROSS SECTIONS

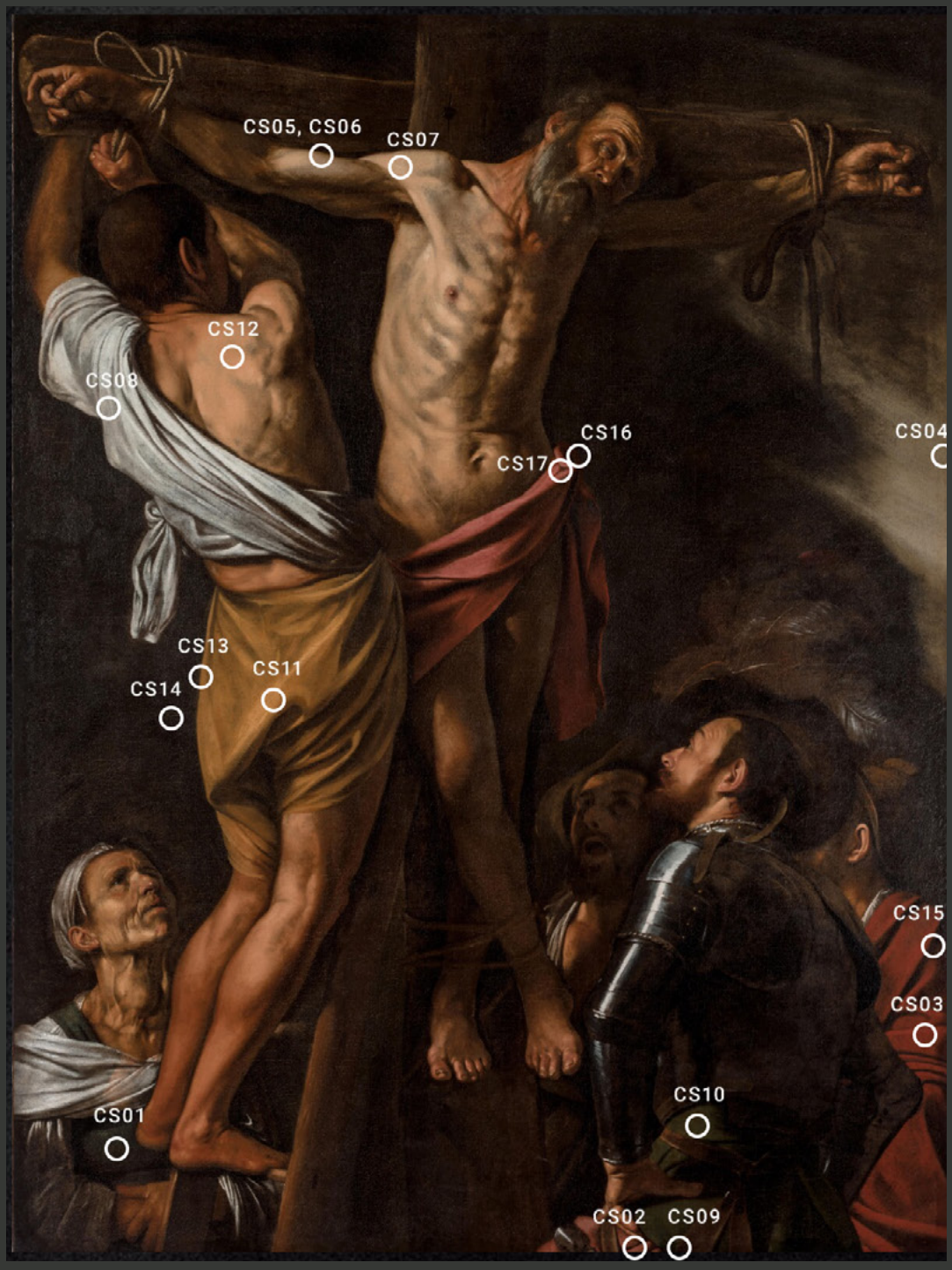
GROUND LAYERS

SEM-BSE IMAGES

RAMAN SPECTROSCOPY

PAINT LAYERS, AFTER CLEANING

SEM-EDS MAPS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

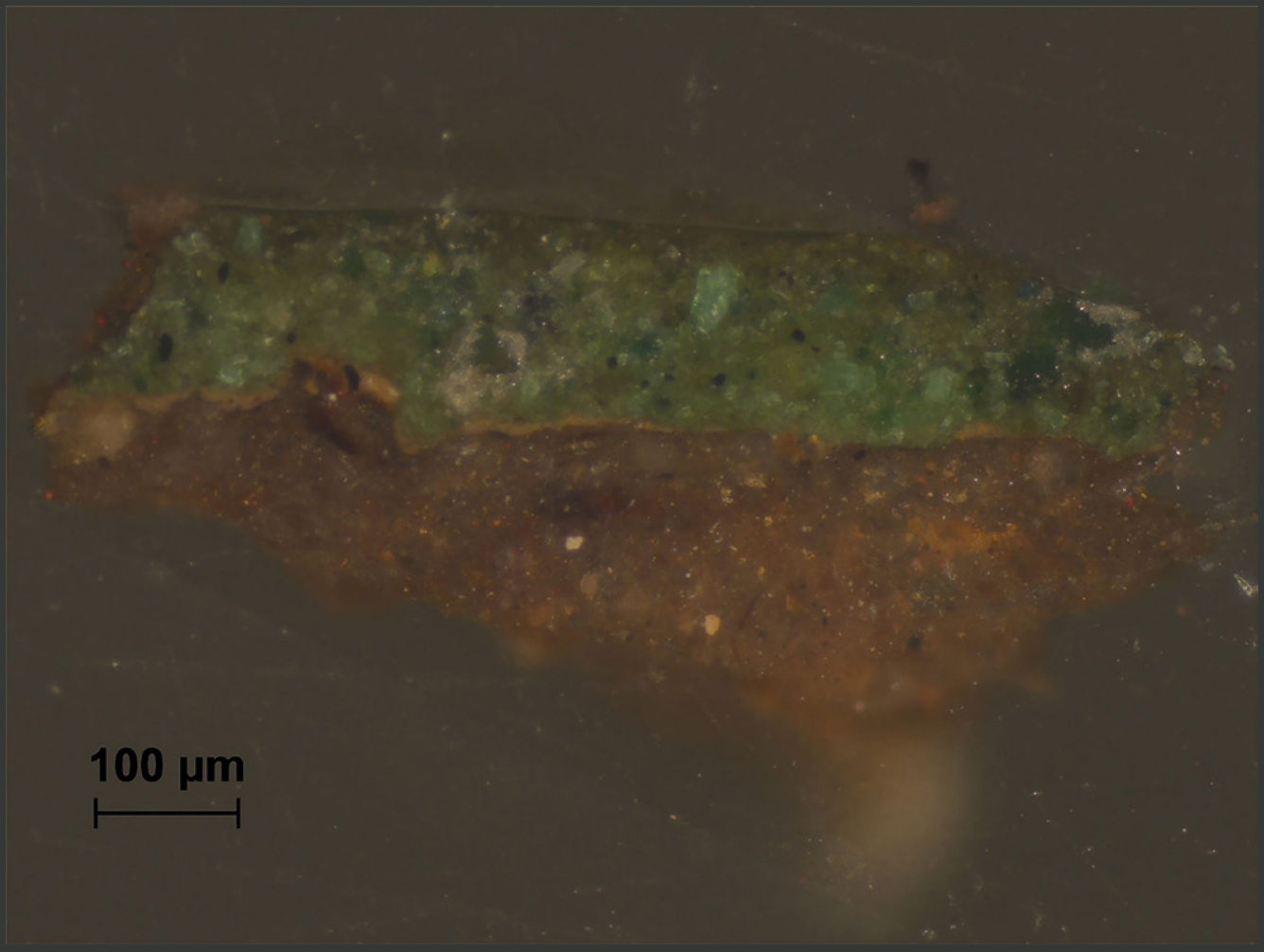
Cross Section 9 (CS09)

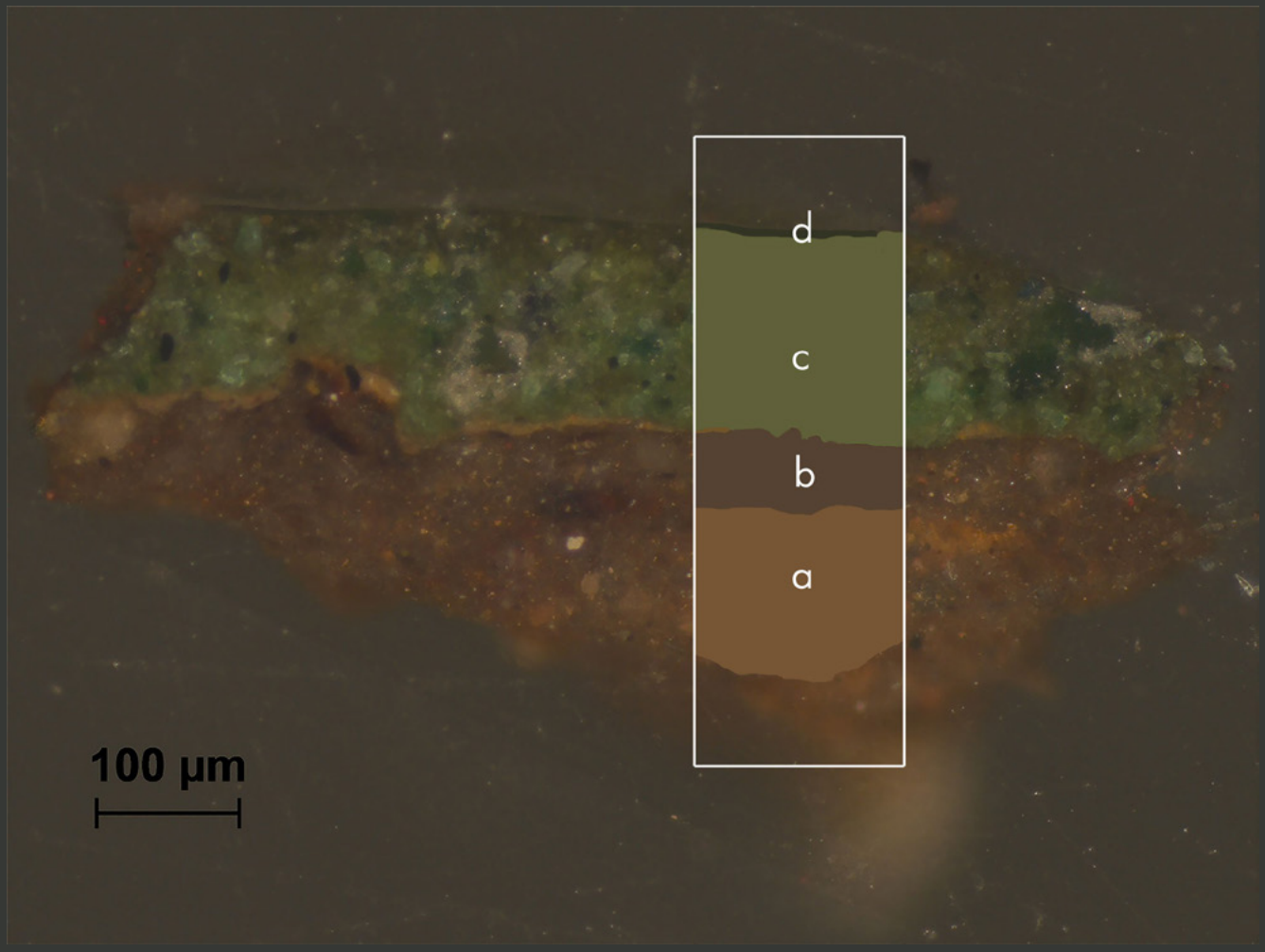
Location: Lower edge of the soldier's garment, after cleaning

This sample was taken to identify the pigments and paint structure used to create the green waistcoat.

CROSS SECTIONS

Normal Light Overlay




d
c
b
a
100 µm

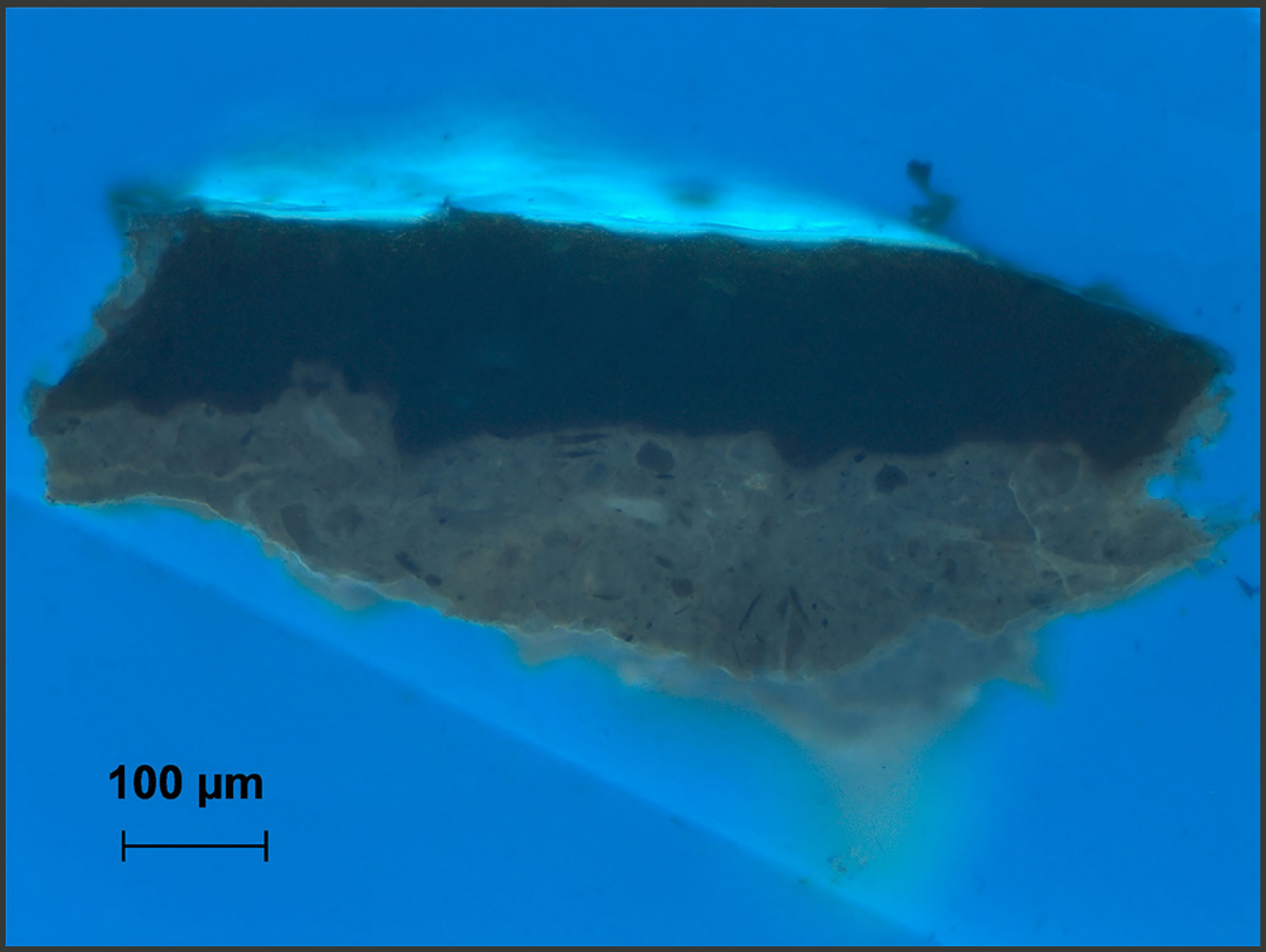
Cross Section 9 (CS09)

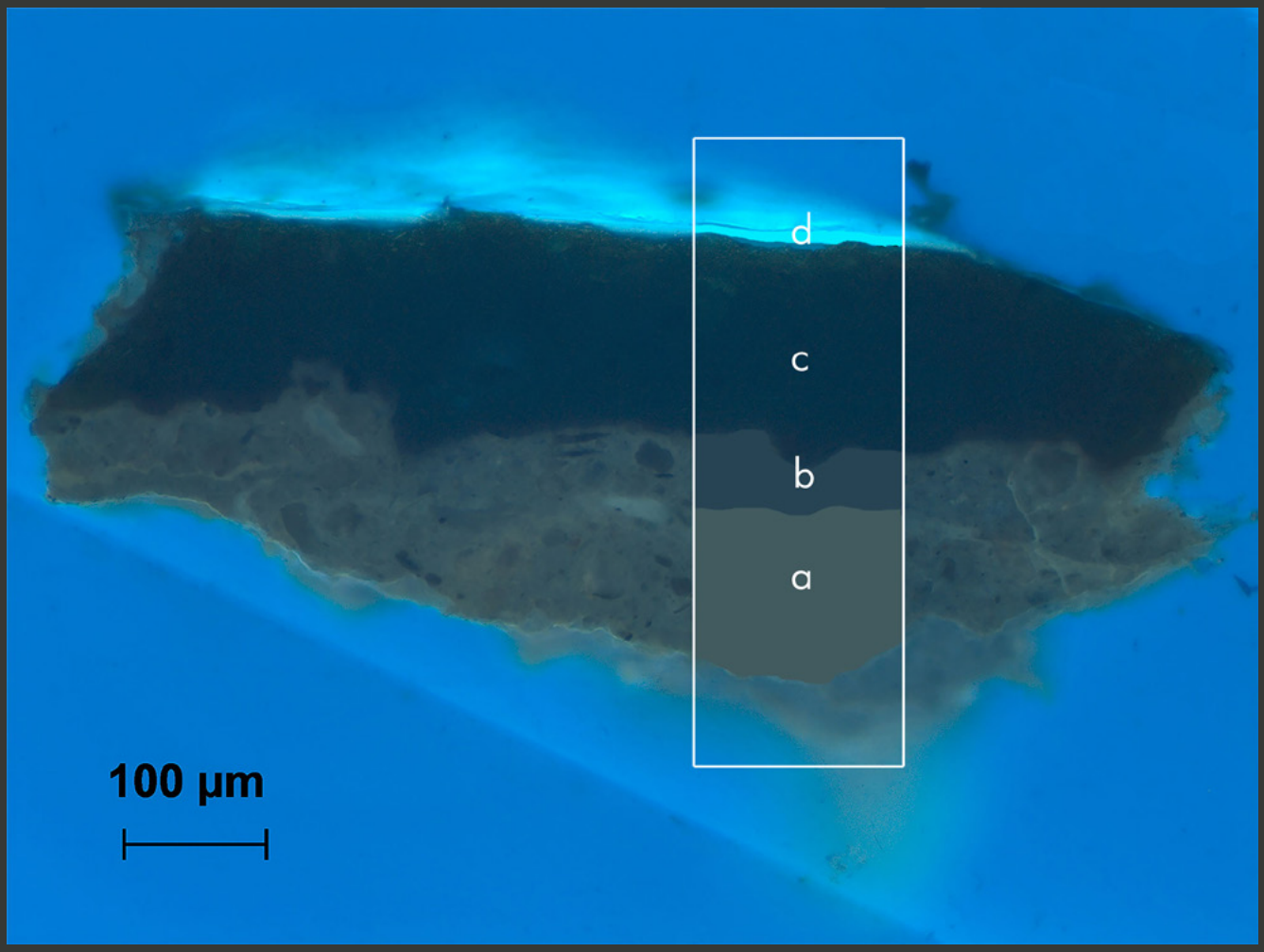
Location: Lower edge of the soldier's garment, after cleaning

This sample was taken to identify the pigments and paint structure used to create the green waistcoat.

Excitation: UV (325-375 nm)
Emission: blue (λ_{em} > 412 nm)

Overlay




d
c
b
a
100 µm

Cross Section 9 (CS09)

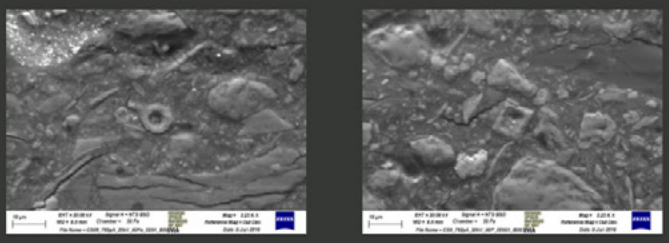
Location: Lower edge of the soldier's garment, after cleaning

GROUND LAYERS

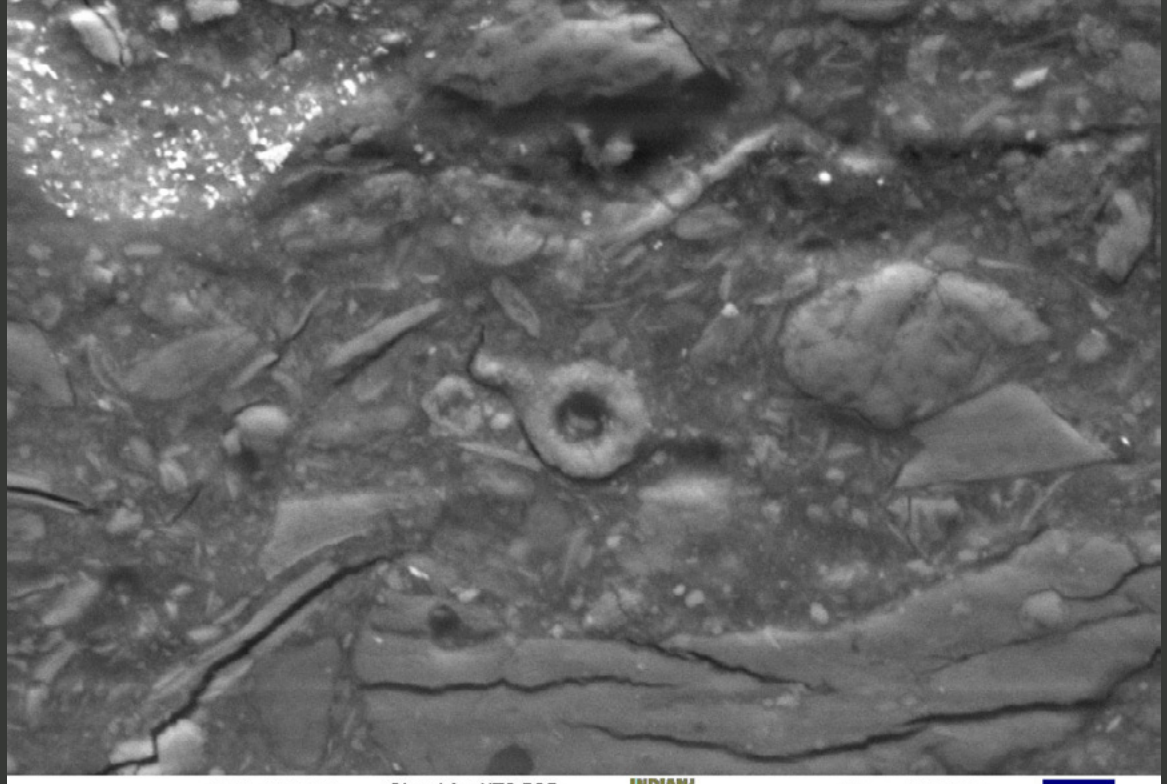
Both ground layers were retained in this sample. According to element mapping with SEM-EDS, there is an even distribution of aluminosilicates; an even and wide distribution of iron; traces of titanium that overlap with particles showing concentrated iron, possibly from ilmenite ($FeTiO_3$); and several large particles of a sodium aluminosilicate. The sparse and faint distribution of phosphorus is likely from bone black.

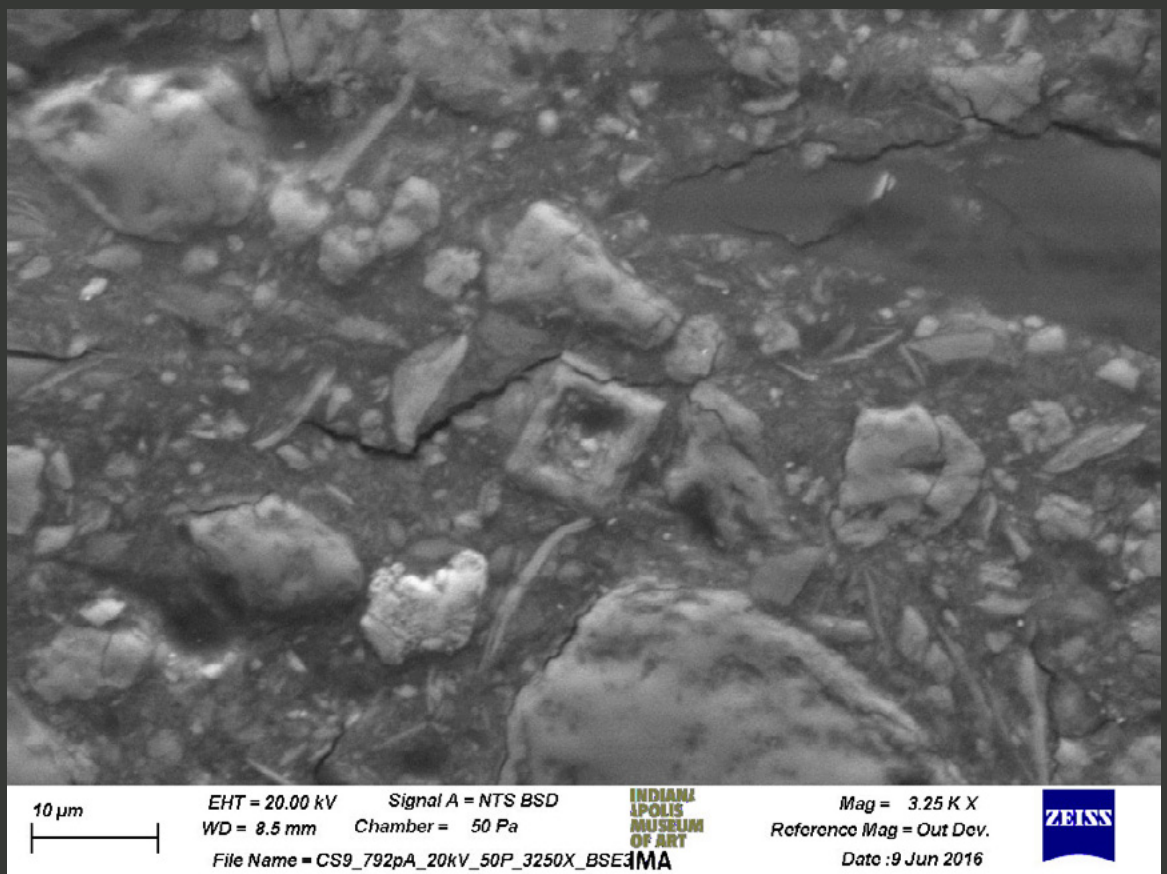
Microfossils are likely present in the ground layer of this sample. A circular microfossil observed at high magnification is similar in structure to an SEM image of a microfossil found in the *Saint Francis in Meditation*(Galleria Nazionale d'Arte Antica, Rome). Other examples observed in this sample exhibited a hollow rectangular structure.

BSE IMAGES



BSE images of possible microfossils found in the lower ground seen at a magnification of 3,250x.

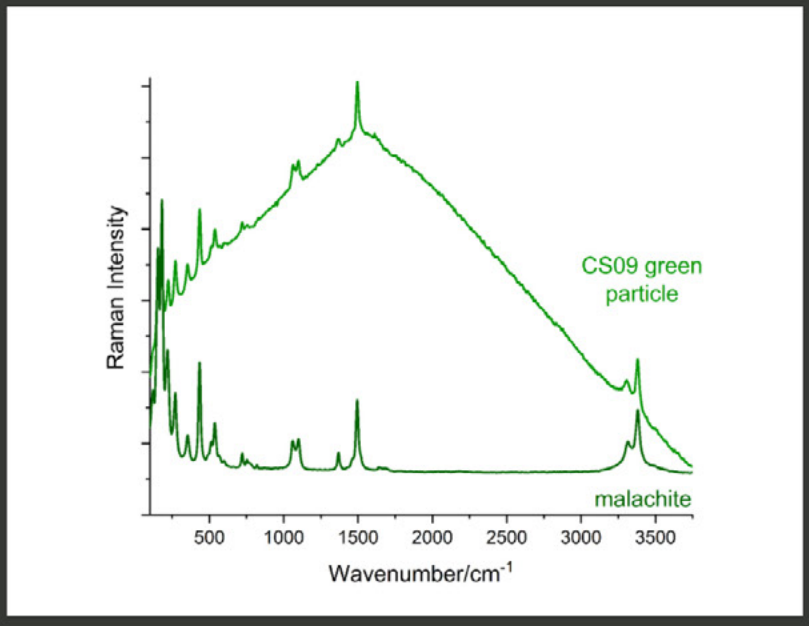

10 µm
EHT = 20.00 kV
WD = 8.5 mm
Signal A = NTS BSD
Chamber = 50 Pa
File Name = CS09_792pA_20kV_50Pa_325X_BSE
INDIANAPOLIS MUSEUM OF ART
IMA
Mag = 3.25 K X
Reference Mag = Out Dev.
Date :9 Jun 2016
ZEISS

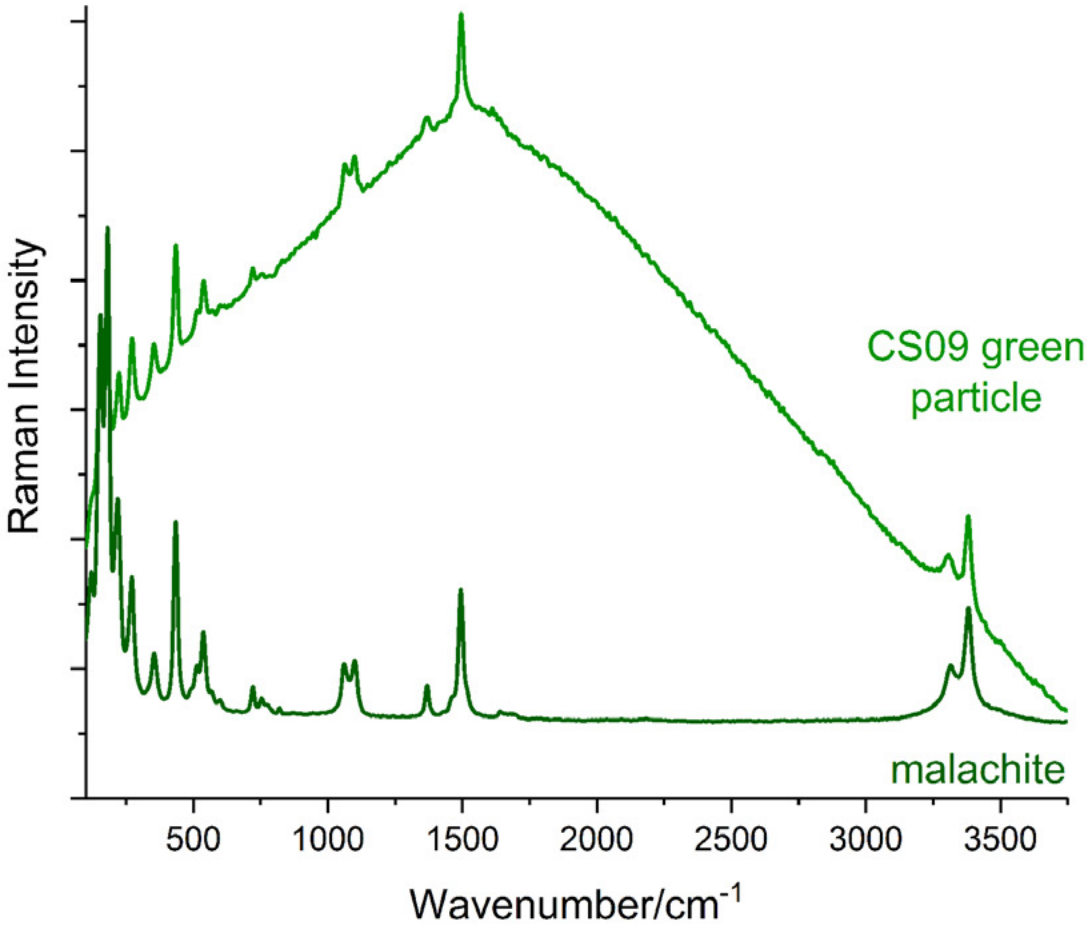

10 µm
EHT = 20.00 kV
WD = 8.5 mm
Signal A = NTS BSD
Chamber = 50 Pa
File Name = CS9_792pA_20kV_50P_3250X_BSE
INDIANAPOLIS MUSEUM OF ART
IMA
Mag = 3.25 K X
Reference Mag = Out Dev.
Date :9 Jun 2016
ZEISS

Cross Section 9 (CS09)

Location: Lower edge of the soldier's garment, after cleaning

RAMAN SPECTROSCOPY



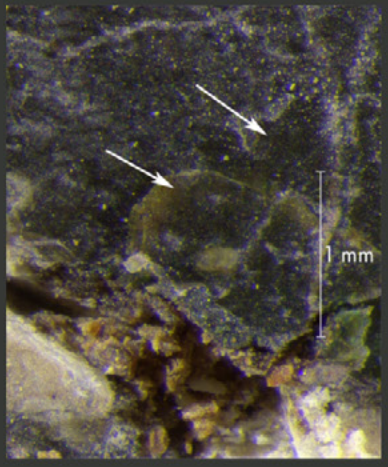

Raman Intensity
CS09 green particle
malachite
500
1000
1500
2000
2500
3000
3500
Wavenumber/cm-1

Cross Section 9 (CS09)

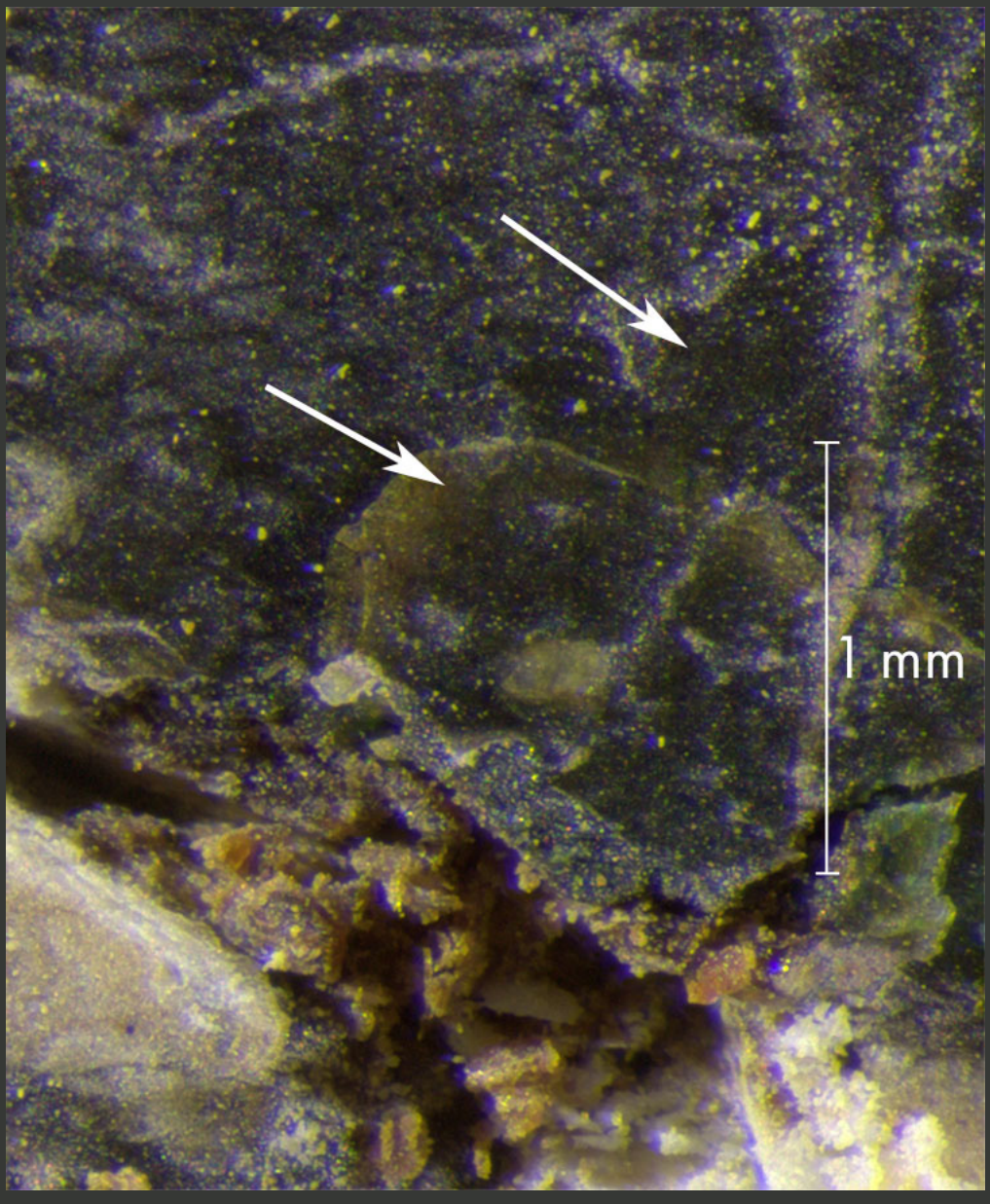
Location: Lower edge of the soldier's garment, after cleaning

PAINT LAYERS, AFTER CLEANING

Based on elemental mapping, the continuous green paint layer (c) has an even distribution of copper-containing pigment confirmed by Raman analysis as malachite, calcium, and oxygen, interspersed with discrete particles containing phosphorus from bone black, sulfur, and a very sparse amount of lead white, except for one prominent particle and a faint distribution where the ground meets the paint layer. Under incandescent illumination, the green paint layer (c) shows a dark brown discoloration, or brown crust, along its top edge. When viewed under UV, the top layer (d) has a bright greenish-blue autofluorescence indicative of a resinous varnish layer. This fluorescing layer is clearly a remnant left behind after cleaning.

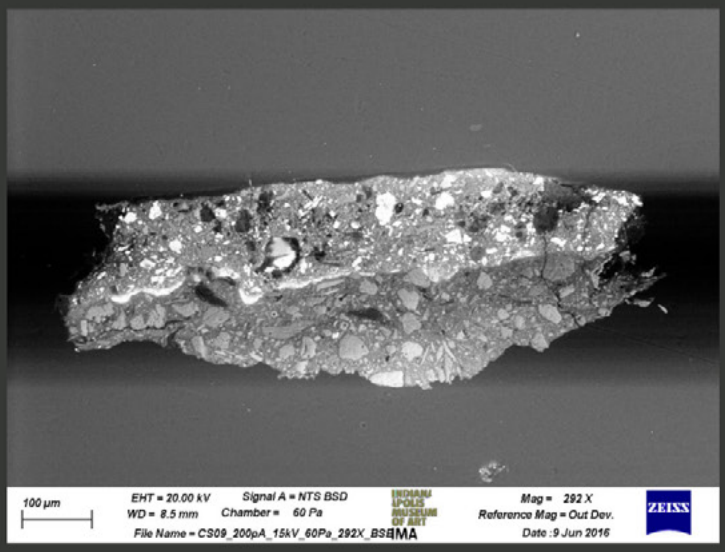


Above, a photographic detail of the sample location shows a glossy translucent surface of the residual varnish patches [arrows pointing to areas of residual varnish]. The brown crust seen along the top of the paint layer (c) is quite separate from (d), and may have been caused by the interaction of the copper pigment (malachite) and the oil binder, possibly producing a type of copper resinate discoloration.

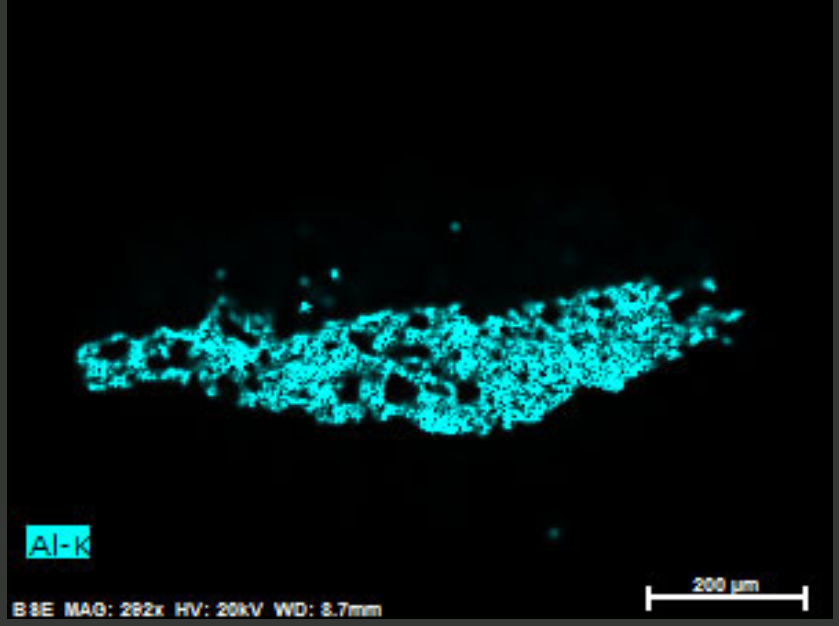

1 mm

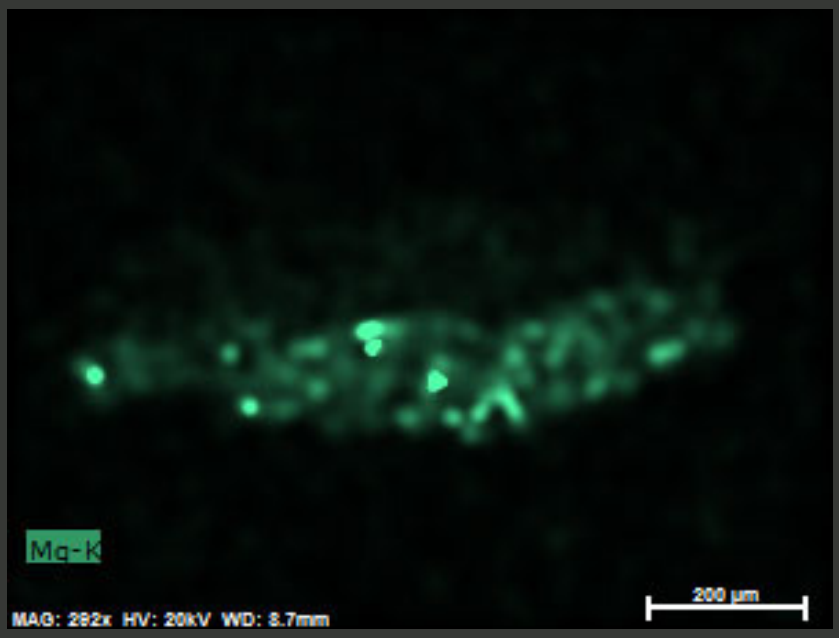
SEM-EDS MAPS

BSE
Na
Mg
Al
Si
P
S
K
Ca
Ti
Fe
Cu
Pb

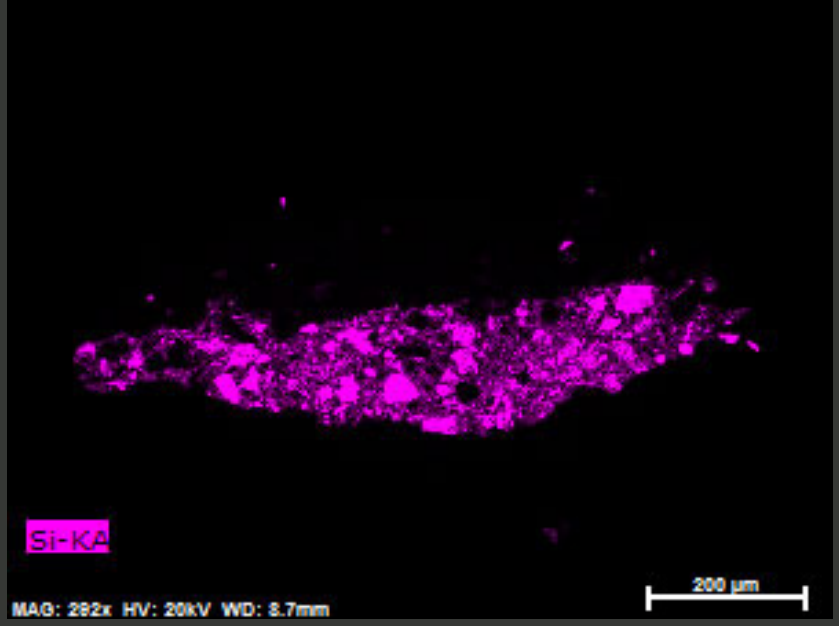


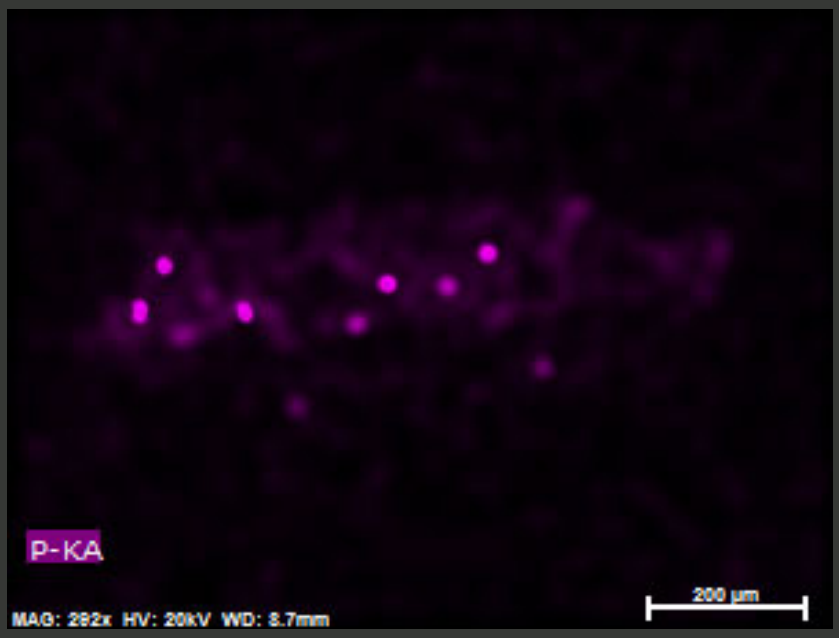
MAG: 282x
HV: 20 kV
WD: 8.7 mm
Scale bar: 200 µm

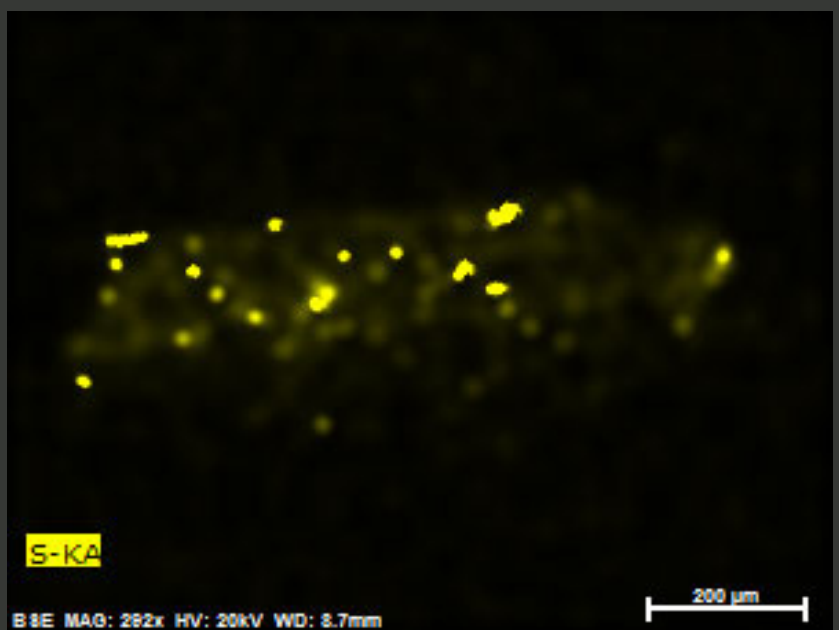

Al-K
B 8E MAG: 282x HV: 20kV WD: 8.7mm
200 µm

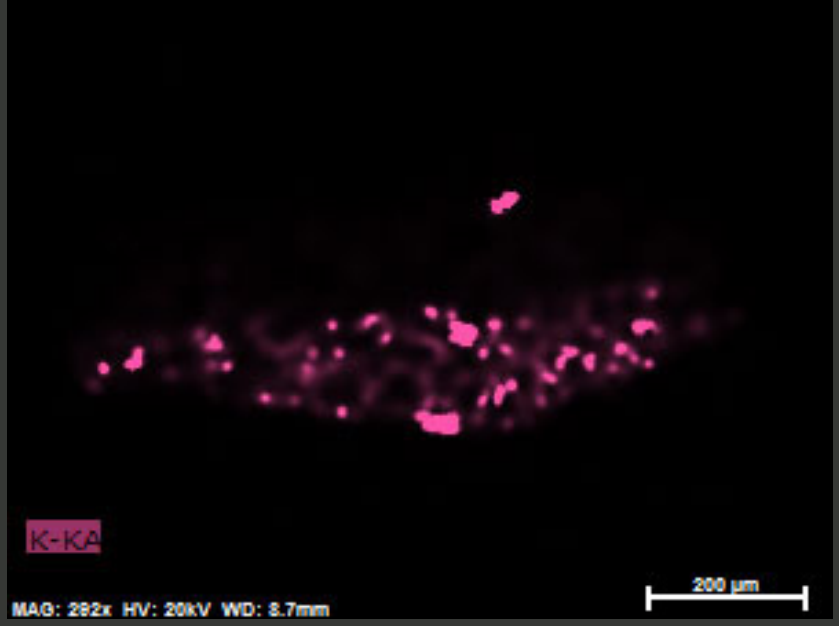

Mg-K
MAG: 282x HV: 20kV WD: 8.7mm
200 µm

Na-KA
MAG: 282x HV: 20kV WD: 8.7mm
200 µm

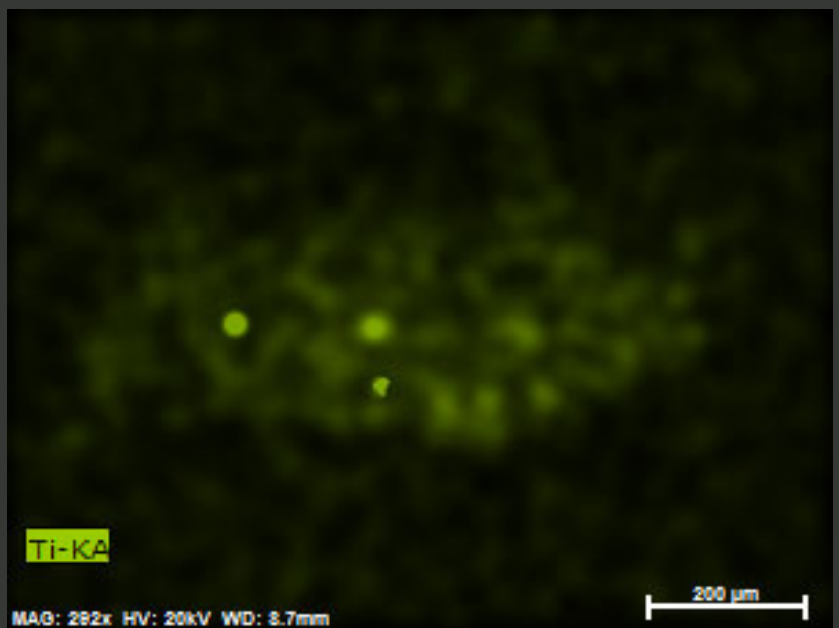

Si-KA
MAG: 282x HV: 20kV WD: 8.7mm
200 µm

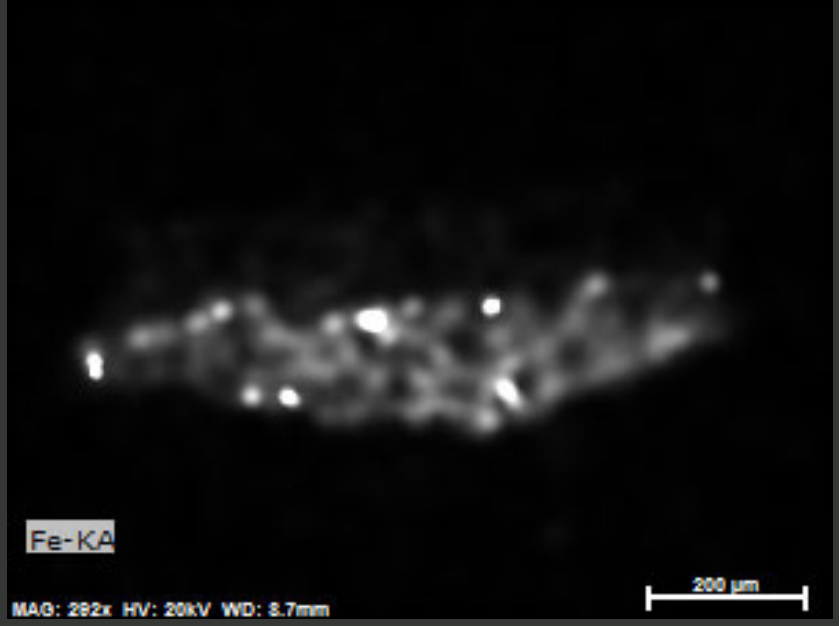

P-KA
MAG: 282x HV: 20kV WD: 8.7mm
200 µm

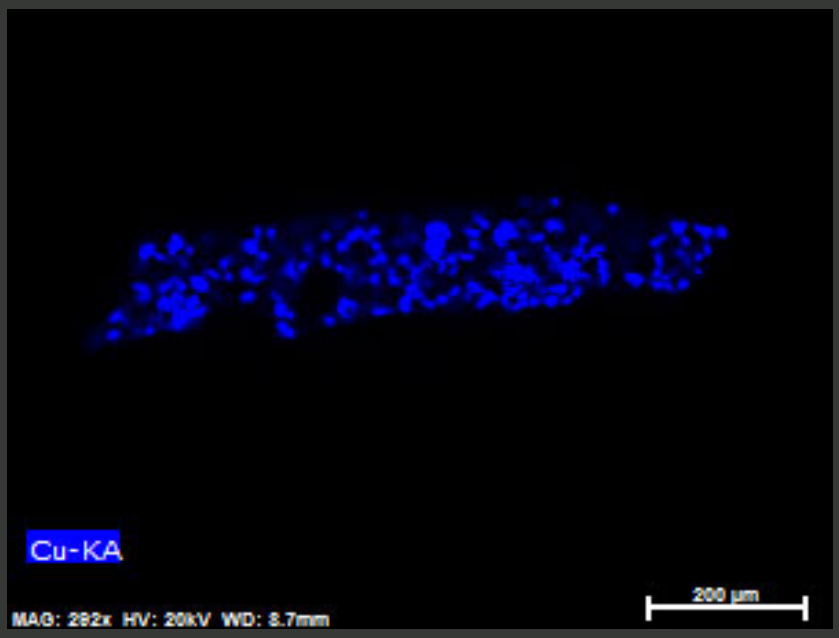

S-KA
B 8E MAG: 282x HV: 20kV WD: 8.7mm
200 µm

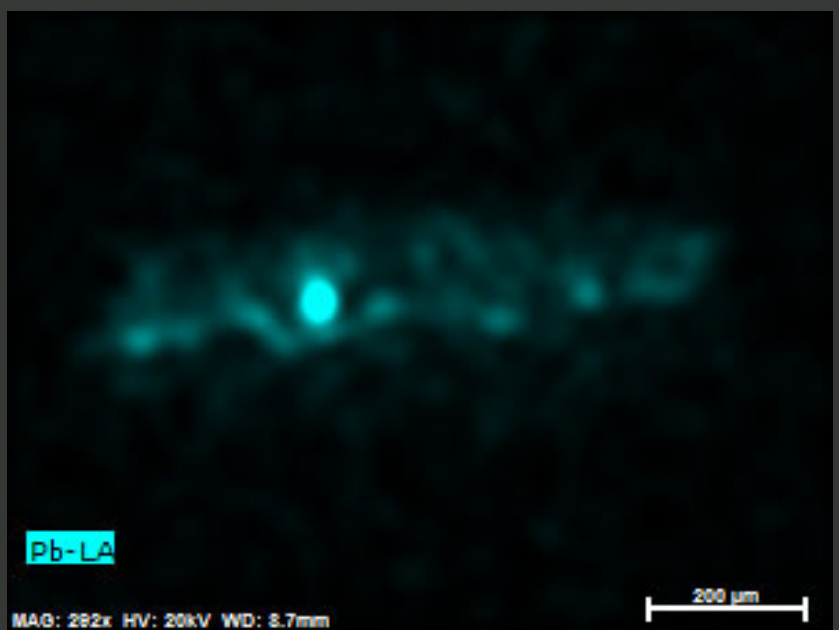

K-KA
MAG: 282x HV: 20kV WD: 8.7mm
200 µm

Ca-KA
MAG: 282x HV: 20kV WD: 8.7mm
200 µm


Ti-KA
MAG: 282x HV: 20kV WD: 8.7mm
200 µm


Fe-KA
MAG: 282x HV: 20kV WD: 8.7mm
200 µm

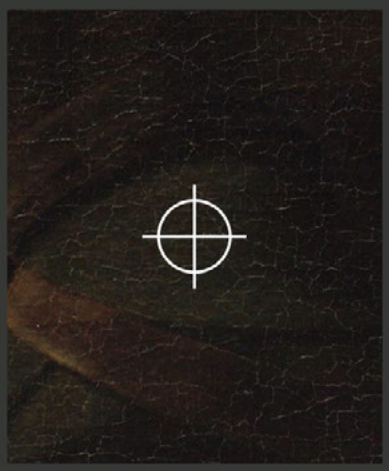

Cu-KA
MAG: 282x HV: 20kV WD: 8.7mm
200 µm

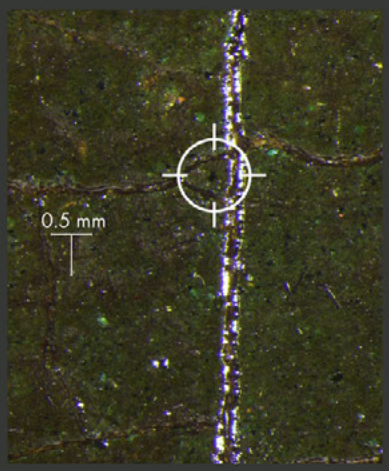

Pb-LA
MAG: 282x HV: 20kV WD: 8.7mm
200 µm

Cross Section 10 (CS10)

Location: Soldier's green waistcoat after cleaning

This sample was taken to verify that the darker brownish-green crust over the lighter malachite pigment particles seen in cross section 9 is a continuous part of the paint layer and not a later addition.

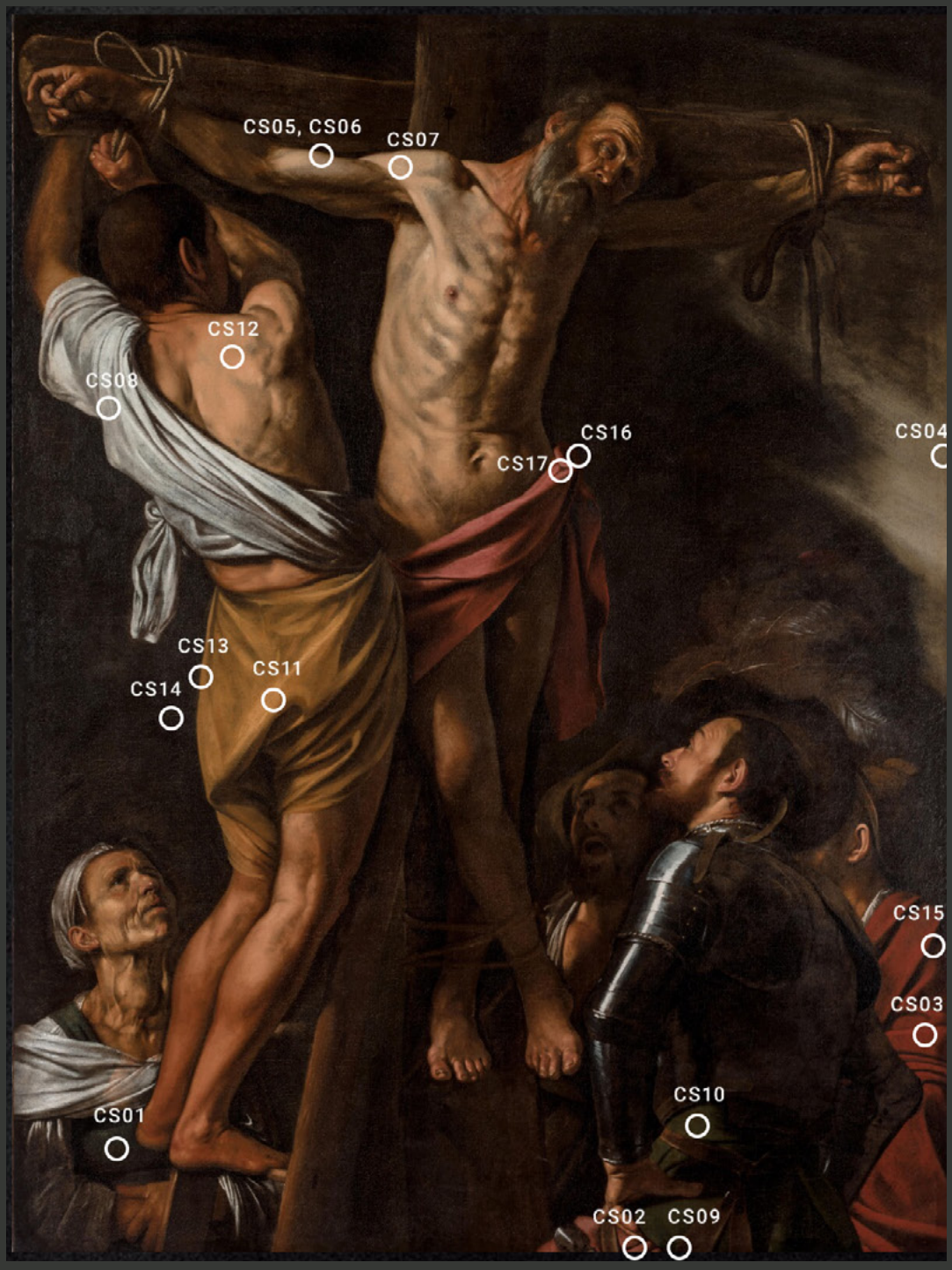




CROSS SECTIONS

GROUND LAYERS

PAINT LAYERS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

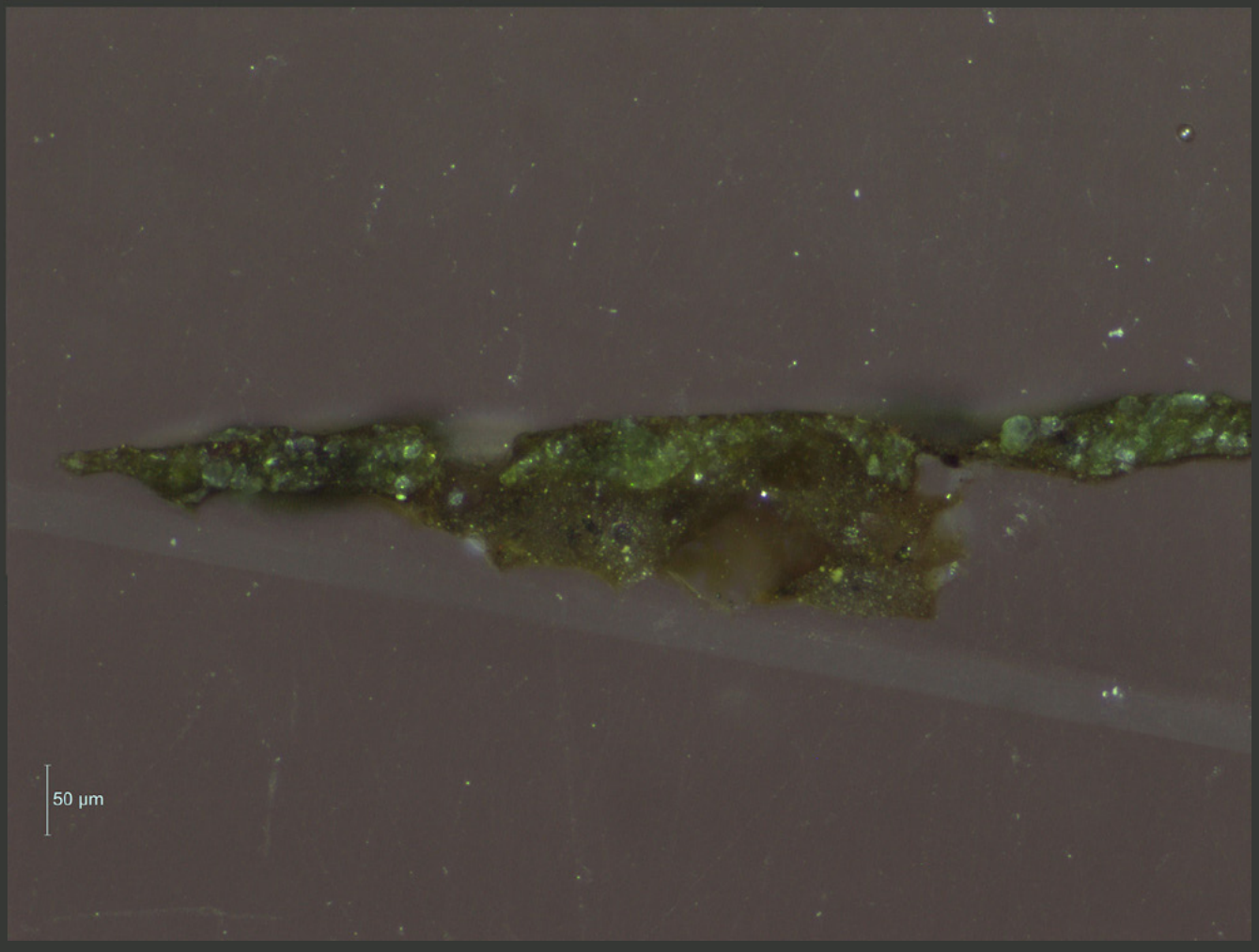
Cross Section 10 (CS10)

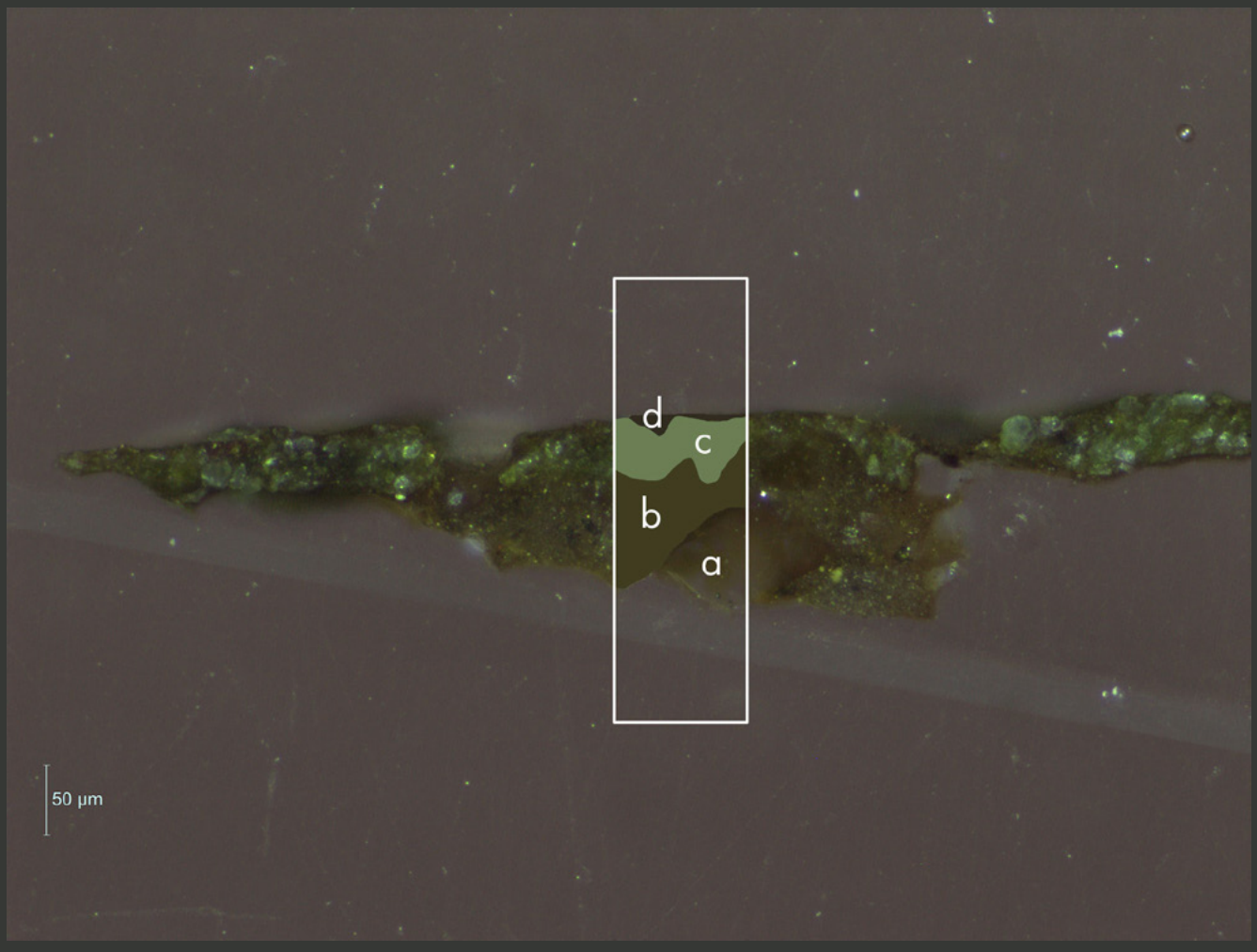
Location: Soldier's green waistcoat after cleaning

This sample was taken to verify that the darker brownish-green crust over the lighter malachite pigment particles seen in cross section 9 is a continuous part of the paint layer and not a later addition.

CROSS SECTIONS

Normal Light Overlay



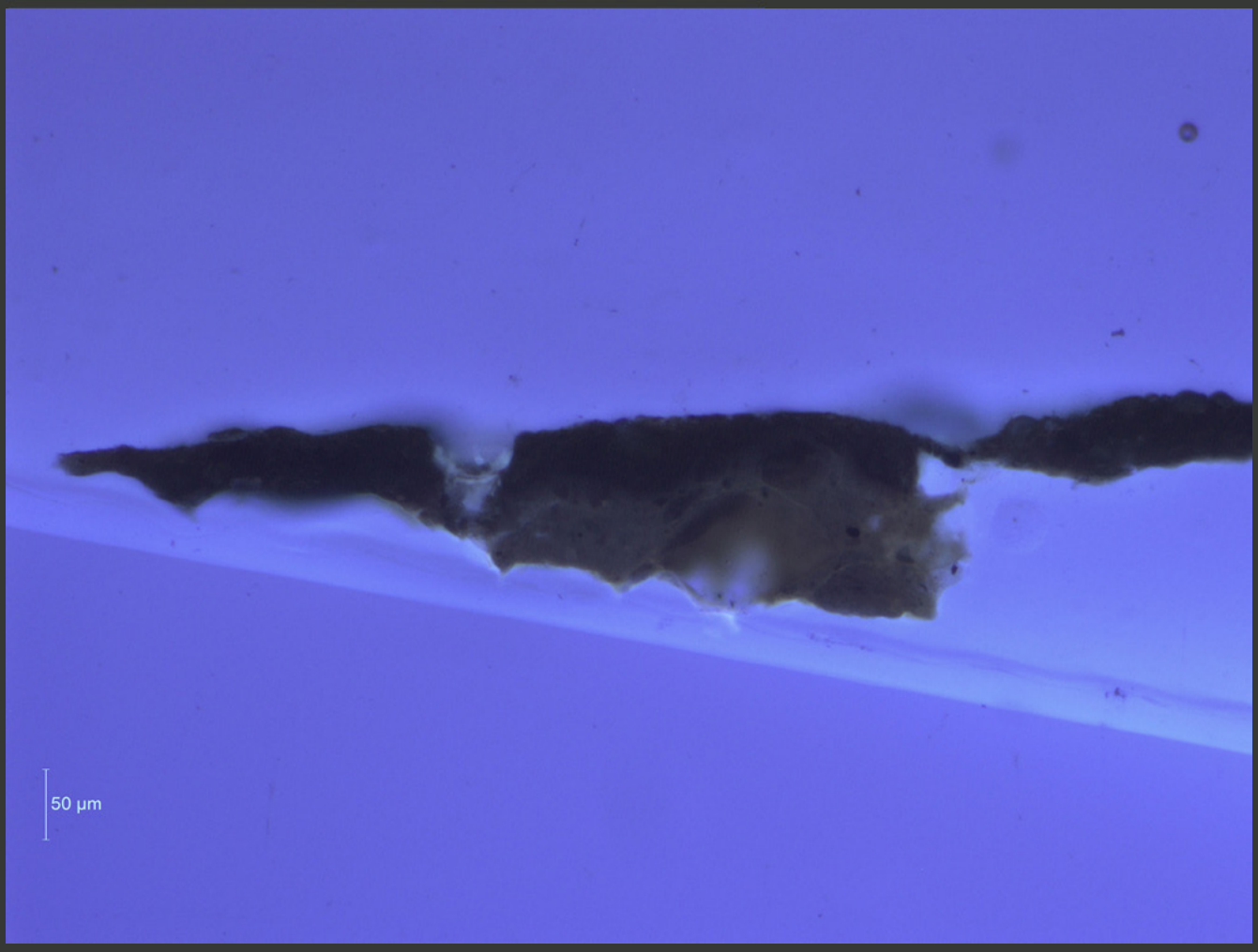

d
c
b
a
50 µm

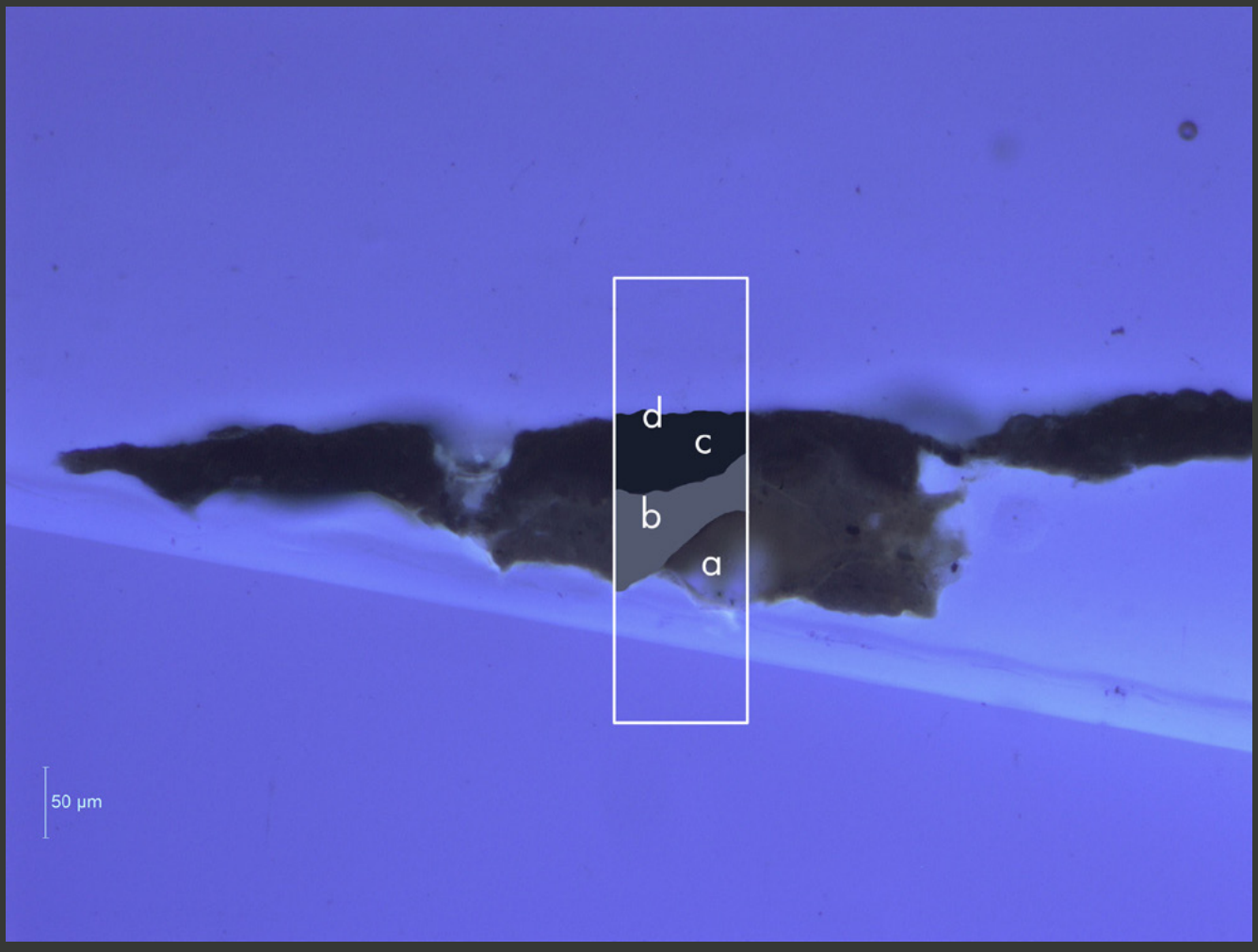
Cross Section 10 (CS10)

Location: Soldier's green waistcoat after cleaning

Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm)

Overlay



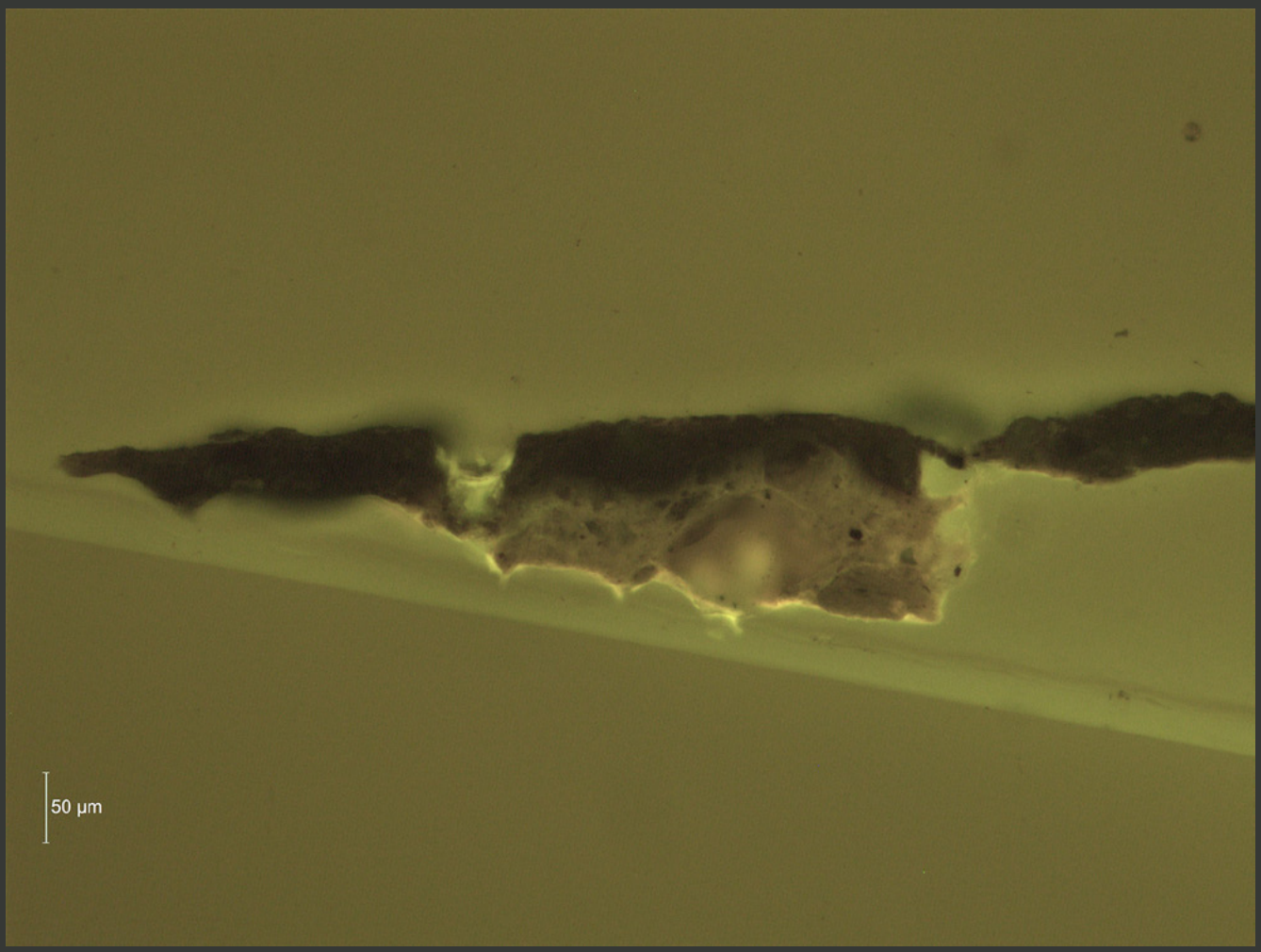

d
c
b
a
50 µm

Cross Section 10 (CS10)

Location: Soldier's green waistcoat after cleaning

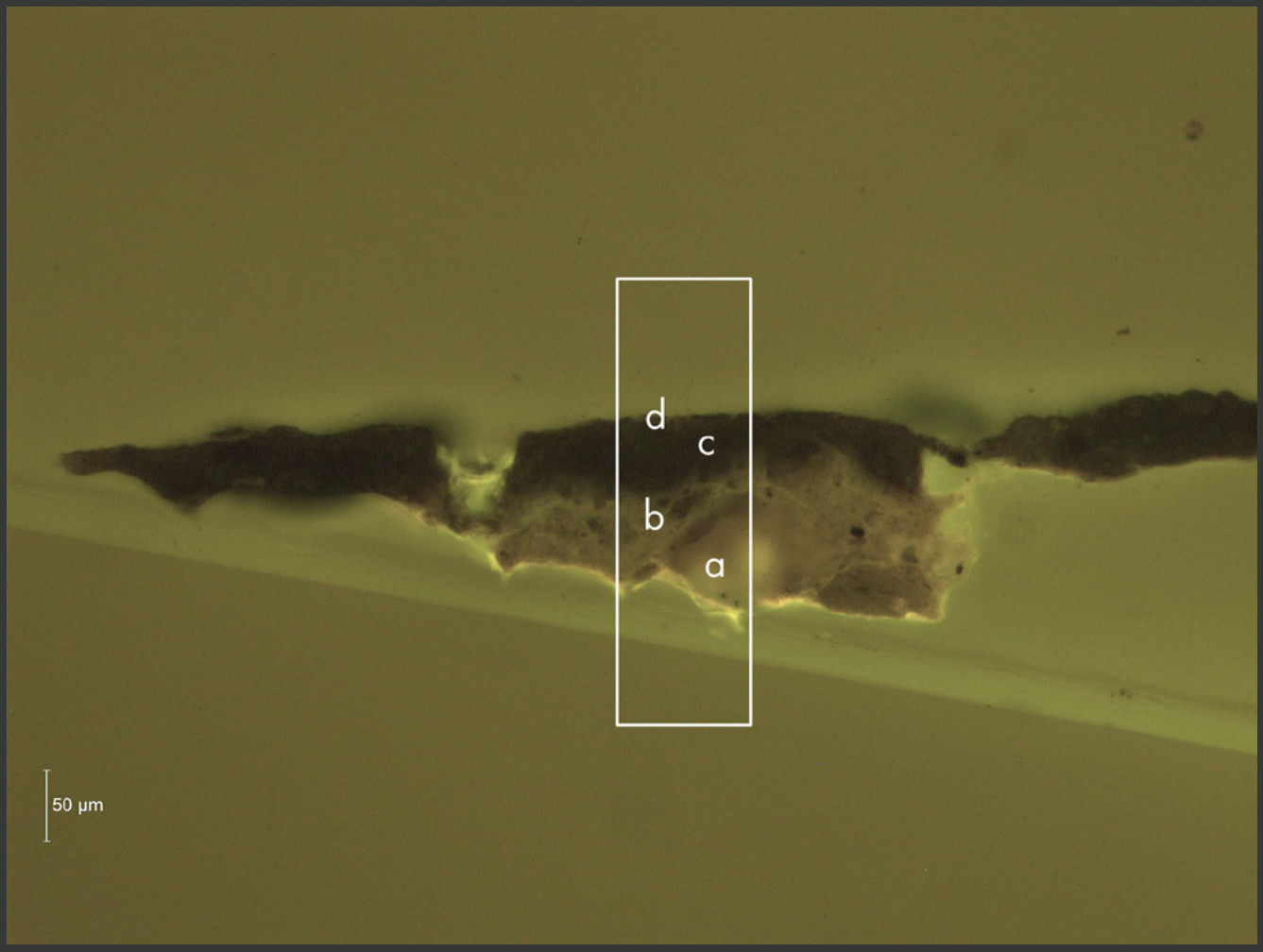
Excitation: blue (450–490 nm)
Emission: green (λ_{em} > 515 nm)

Overlay



GROUND LAYERS

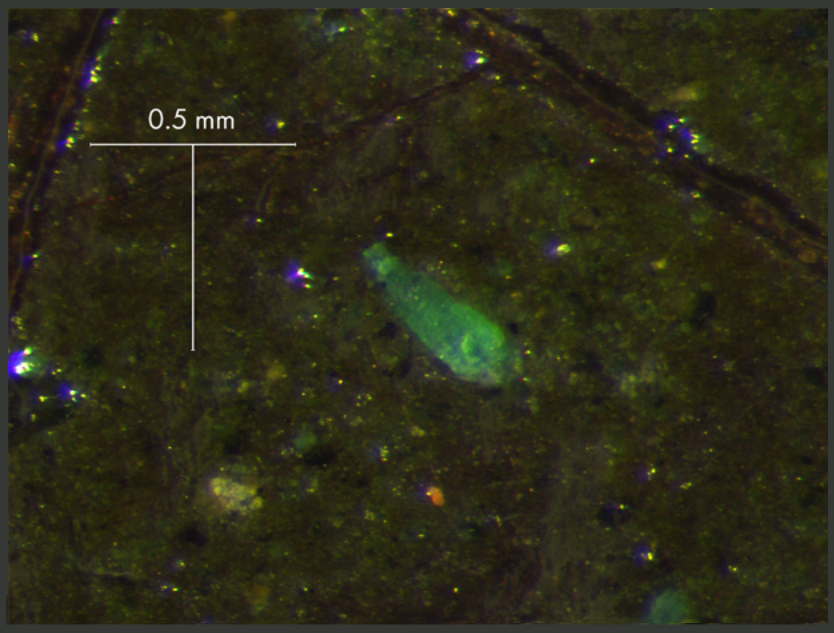
It appears that only a portion of the upper ground was retained during the sampling, as the lower ground is completely missing. Under UV, layer (b) fluoresces slightly lighter than the paint layer (c) and its crust (d). A large translucent particle is present (a), which appears to be part of the upper ground.


d
c
b
a
50 µm

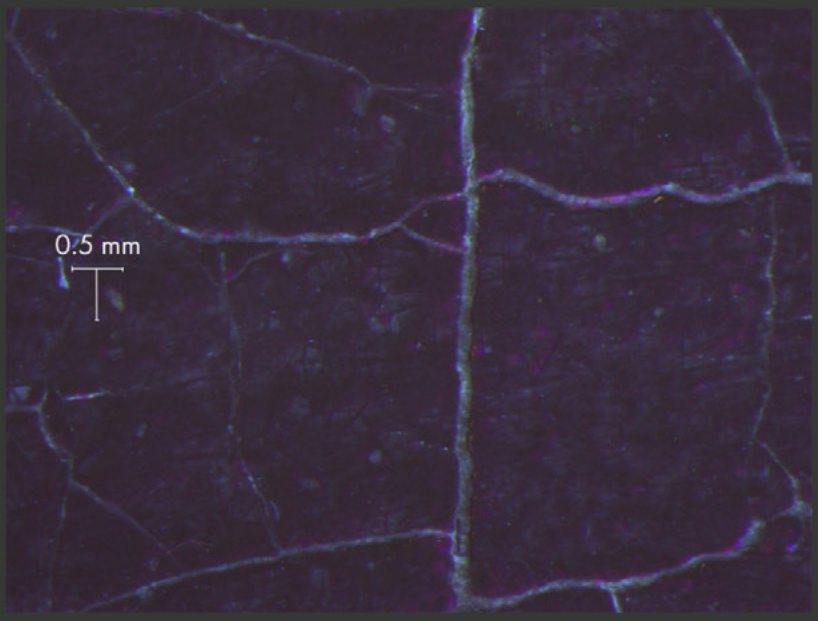
PAINT LAYERS

When viewed under normal light, sample 10, taken from the green waistcoat (between the armor and belt) after treatment, has a dark brownish-green crust (d) along the top edge of the paint layer. This crust also appears to be part of the green paint layer, similar to cross section 9. Under UV, the brown crust appears to be part of the green paint layer and shows no physical separation. However, because cross section 10 was taken after removal of all the previous varnish layers, the autofluorescent varnish layer seen in cross section 9 is completely absent.

Curiously, close inspection of the paint surface under the microscope with UV irradiation reveals a sporadic, extremely thin, crazed, and weak autofluorescence over some areas of the green waistcoat. This fluorescence is much thinner and weaker than the thicker autofluorescent varnish remnants seen in layer (d) of cross section 9. It is possible that the weakly autofluorescent crazing near cross section 10 was not captured in the sample.



In the area of the soldier's waistcoat, a field of semitransparent brown and smaller particles surround a large, protruding light green malachite particle. A photomicrograph of the paint surface shows many of the lighter green (malachite) pigment particles protruding through this thin discolored crust.

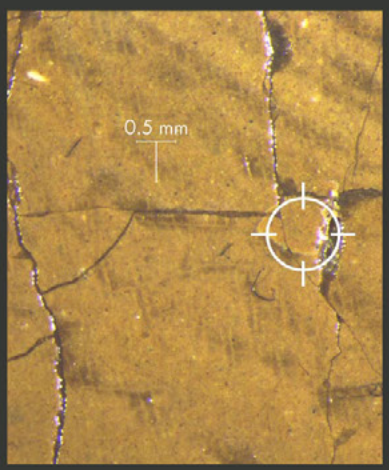


An extremely thin, sporadic, crazed, and weak autofluorescence over some areas of the green waistcoat can be seen in this UV image of the painting's surface after cleaning. Fluorescing varnish residues remain deep in the crack structure.

Cross Section 11 (CS11)

Location: Yellow trousers of the executioner on the ladder

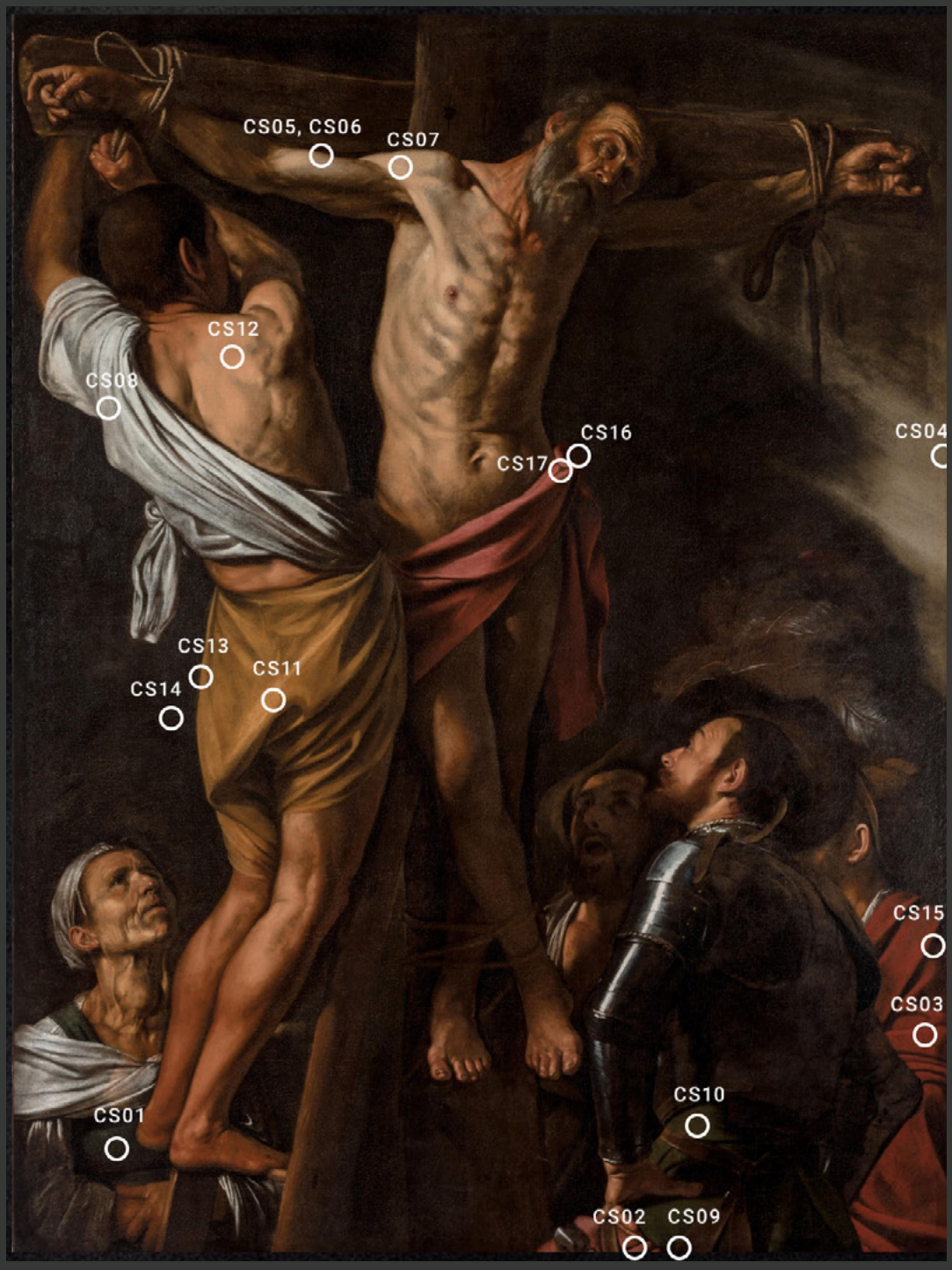
This sample was taken after treatment to confirm the presence of a lead-tin yellow pigment in the trousers. Raman spectroscopy confirmed that the light yellow glassy particles are lead-tin yellow type II ($Pb(Sn,Si)O_3$) and the darker yellow translucent particles are yellow ochre. Small particles of lead white, also confirmed by Raman analysis, are interspersed among the two yellow pigments. Both of the ground layers are missing from this sample, because the paint cleaved away from the upper ground layer during sampling.



CROSS SECTIONS

RAMAN SPECTROSCOPY

SEM-EDS MAPS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

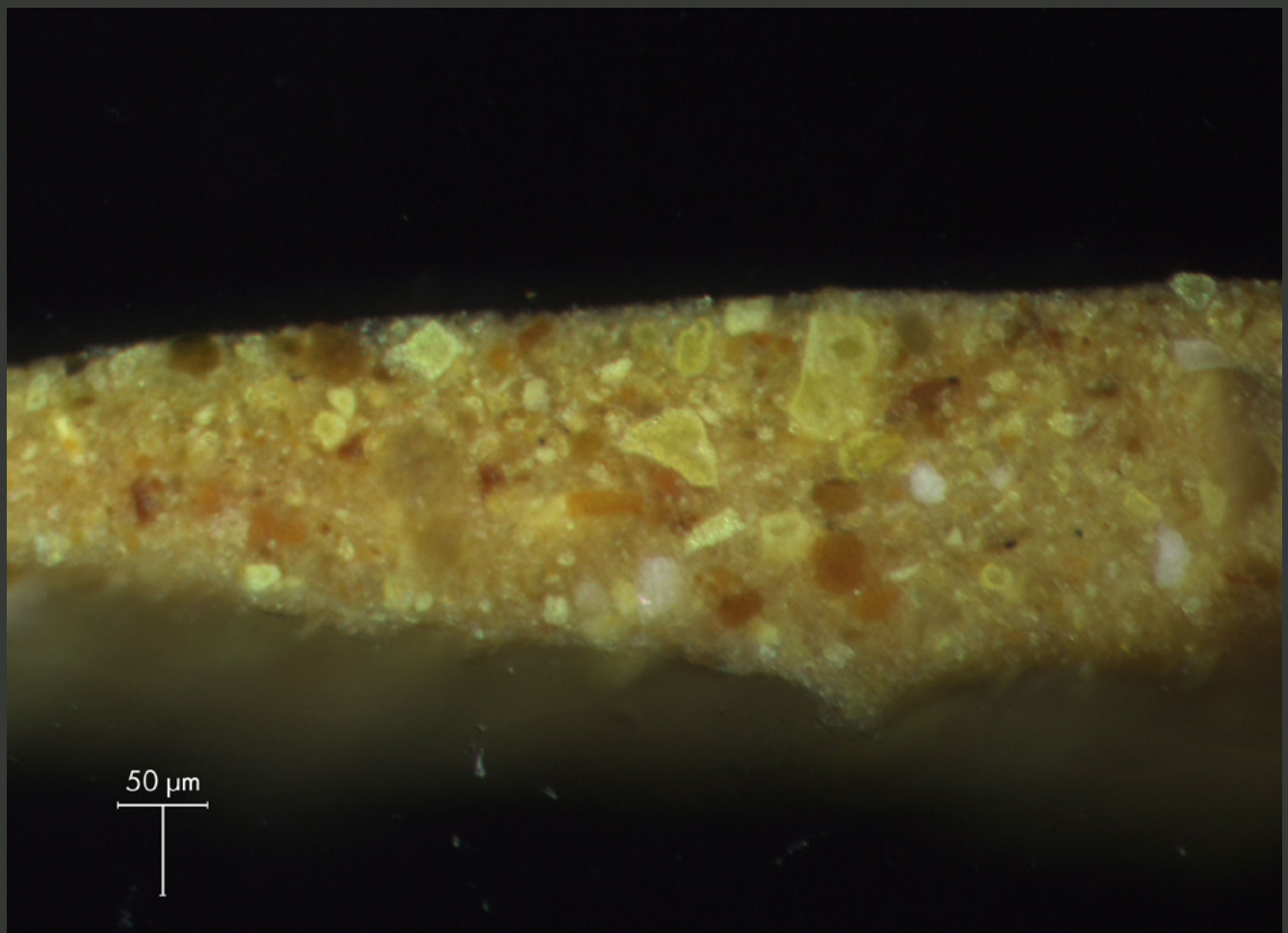
Cross Section 11 (CS11)

Location: Yellow trousers of the executioner on the ladder

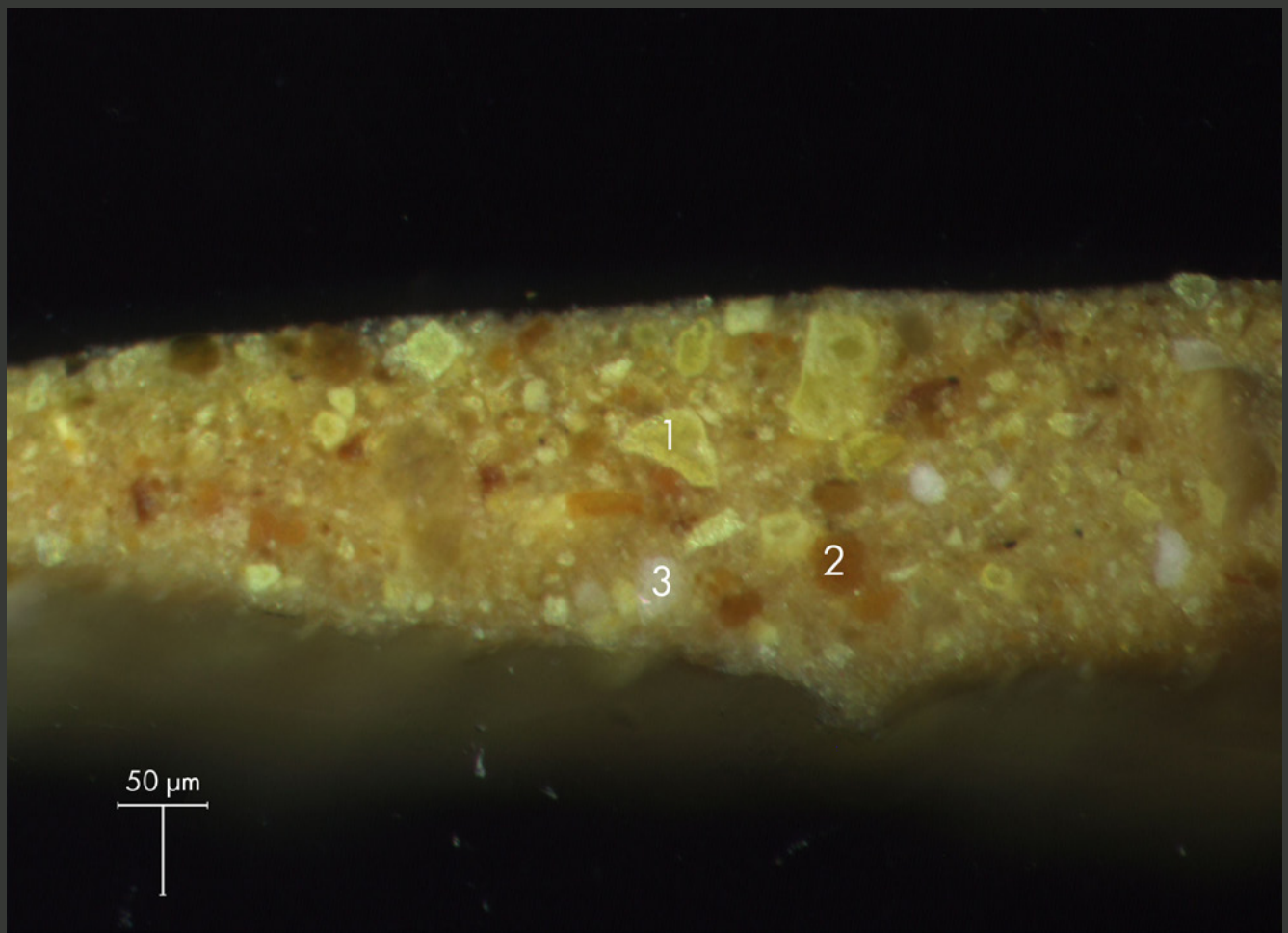
This sample was taken after treatment to confirm the presence of a lead-tin yellow pigment in the trousers. Raman spectroscopy confirmed that the light yellow glassy particles are lead-tin yellow type II ($Pb(Sn,Si)O_3$) and the darker yellow translucent particles are yellow ochre. Small particles of lead white, also confirmed by Raman analysis, are interspersed among the two yellow pigments. Both of the ground layers are missing from this sample, because the paint cleaved away from the upper ground layer during sampling.

CROSS SECTIONS

Normal Light Overlay



(1) Lead-tin yellow type II
(2) Yellow ochre
(3) Lead white particle (not shown in Raman graph)

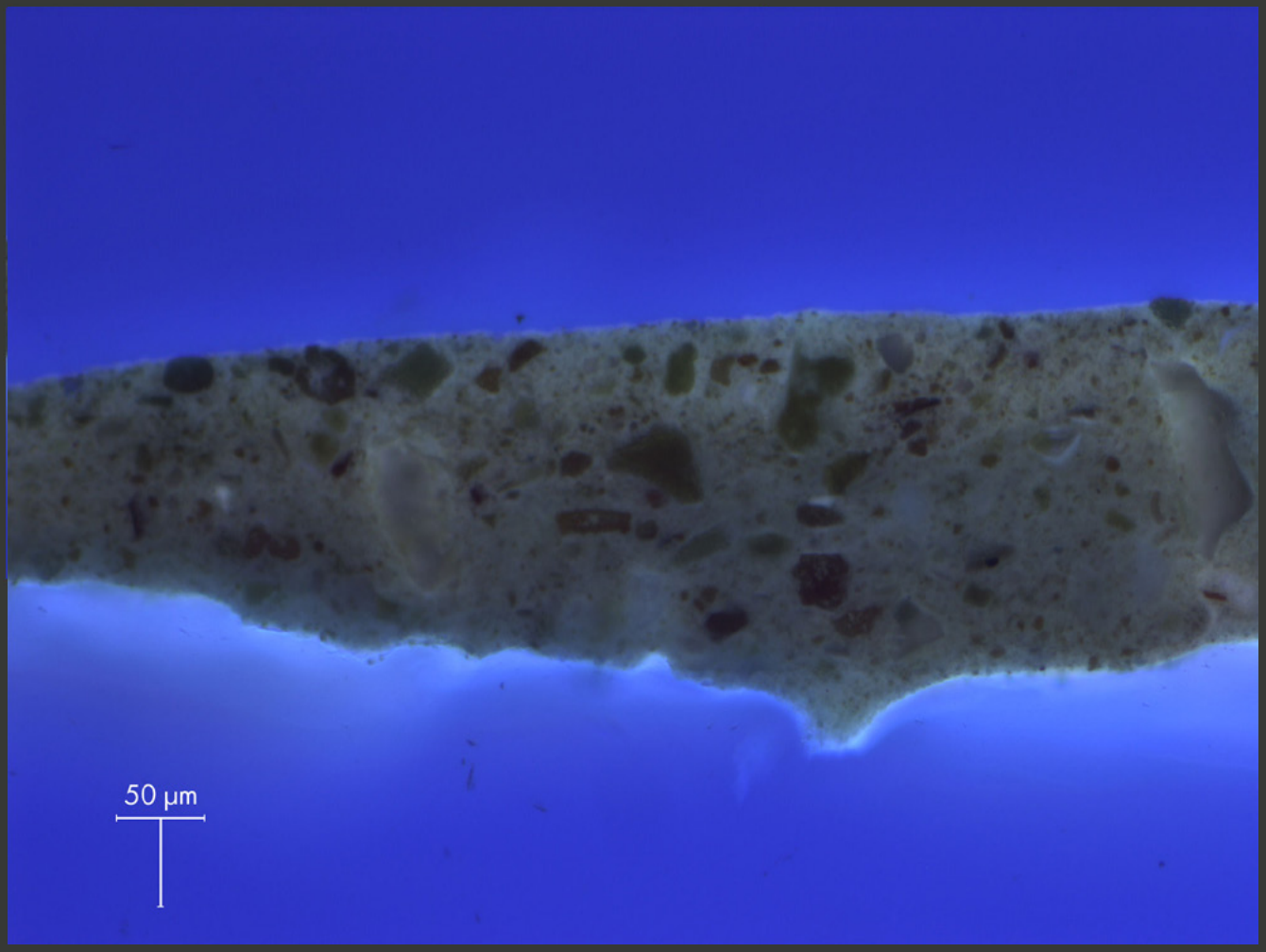


Cross Section 11 (CS11)

Location: Yellow trousers of the executioner on the ladder

(1) Lead-tin yellow type II
(2) Yellow ochre
(3) Lead white particle (not shown in Raman graph)

Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm)

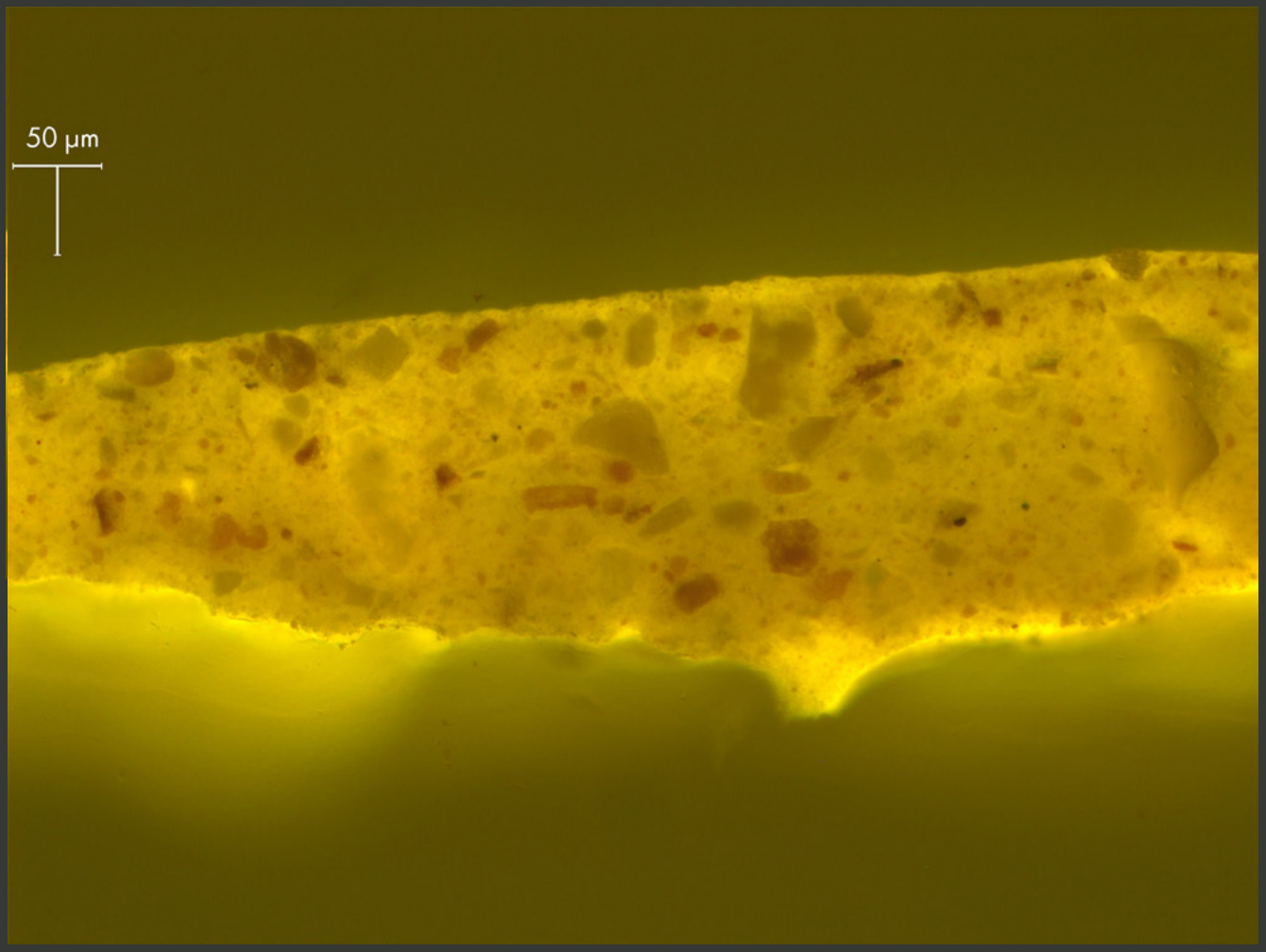


Cross Section 11 (CS11)

Location: Yellow trousers of the executioner on the ladder

(1) Lead-tin yellow type II
(2) Yellow ochre
(3) Lead white particle (not shown in Raman graph)

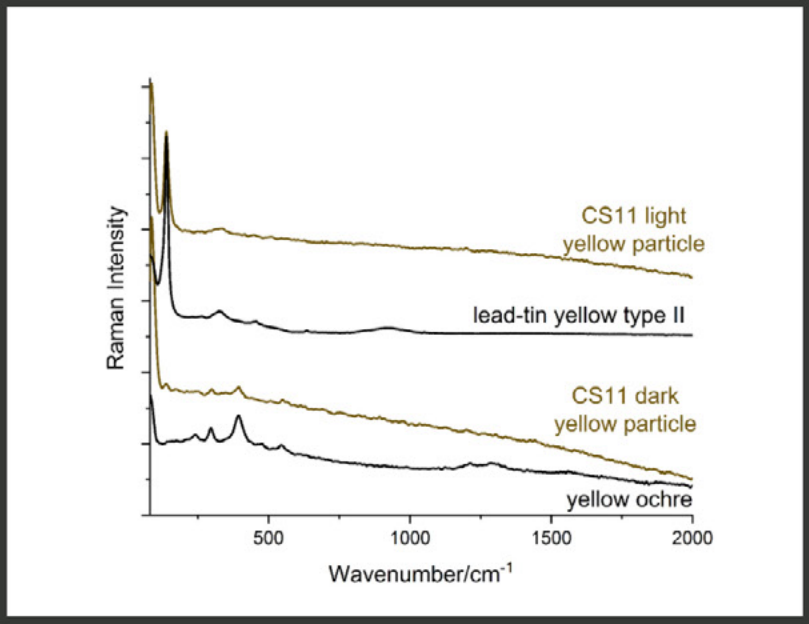
Excitation: blue (450–490 nm)
Emission: green (λ_{em} > 515 nm)

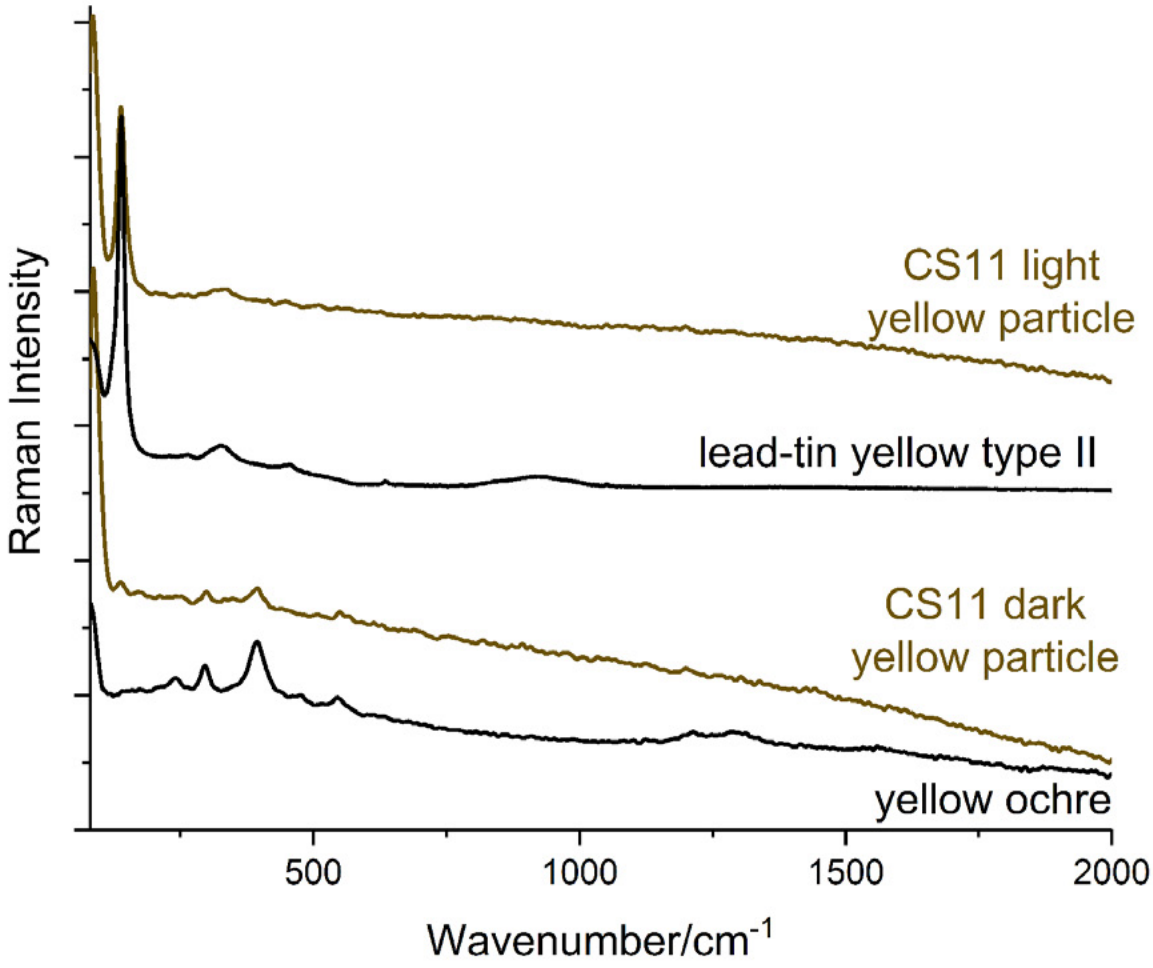


Cross Section 11 (CS11)

Location: Yellow trousers of the executioner on the ladder

RAMAN SPECTROSCOPY




Raman Intensity
CS11 light
yellow particle
lead-tin yellow type II
CS11 dark
yellow particle
yellow ochre
500
1000
1500
2000
Wavenumber/cm-1

Cross Section 11 (CS11)

Location: Yellow trousers of the executioner on the ladder

SEM-EDS MAPS

BSE

Mg

Al

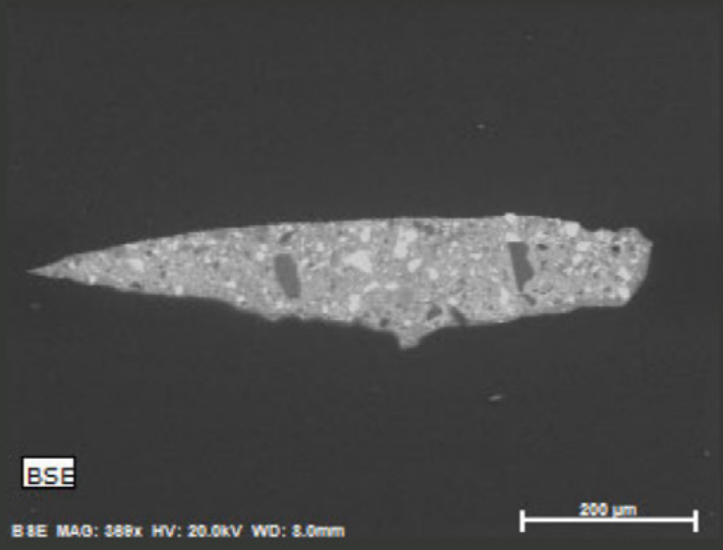
Si

Ca

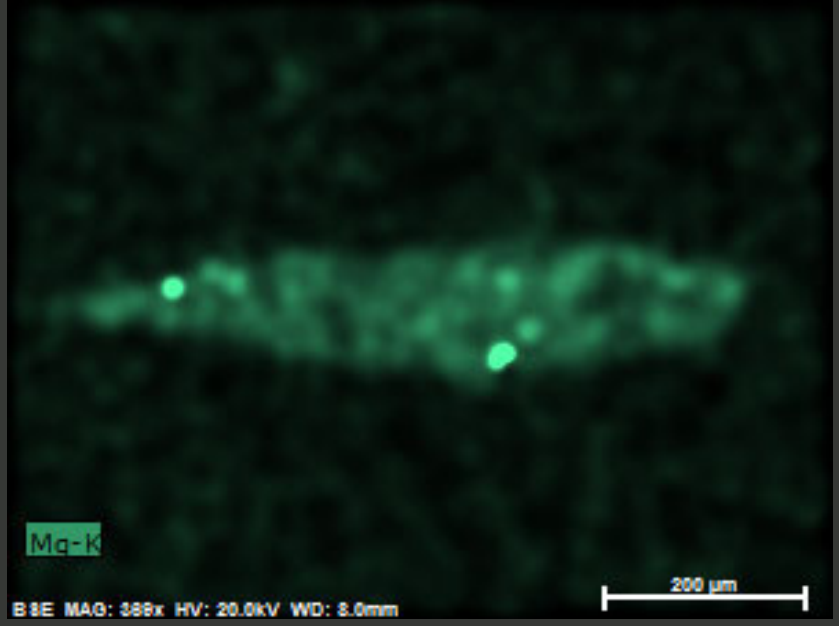
Fe

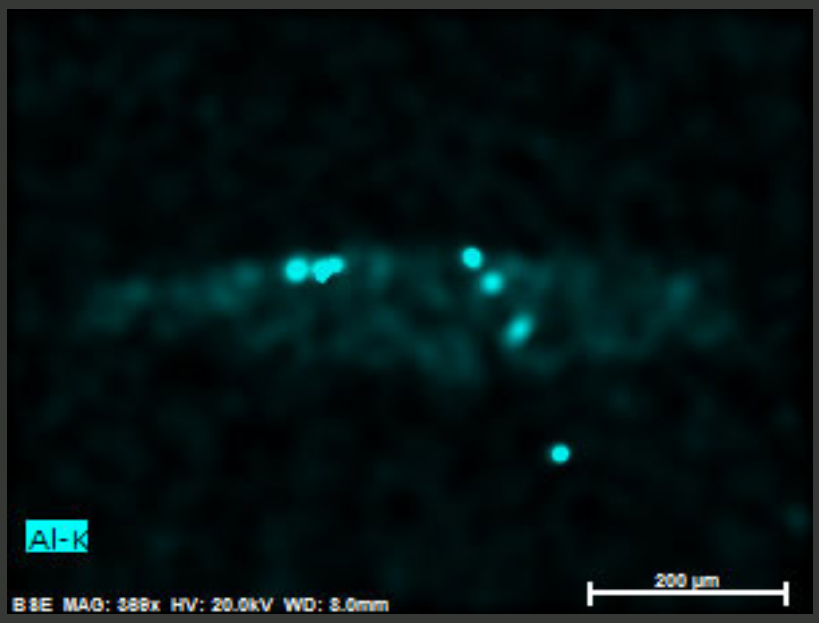
Sn

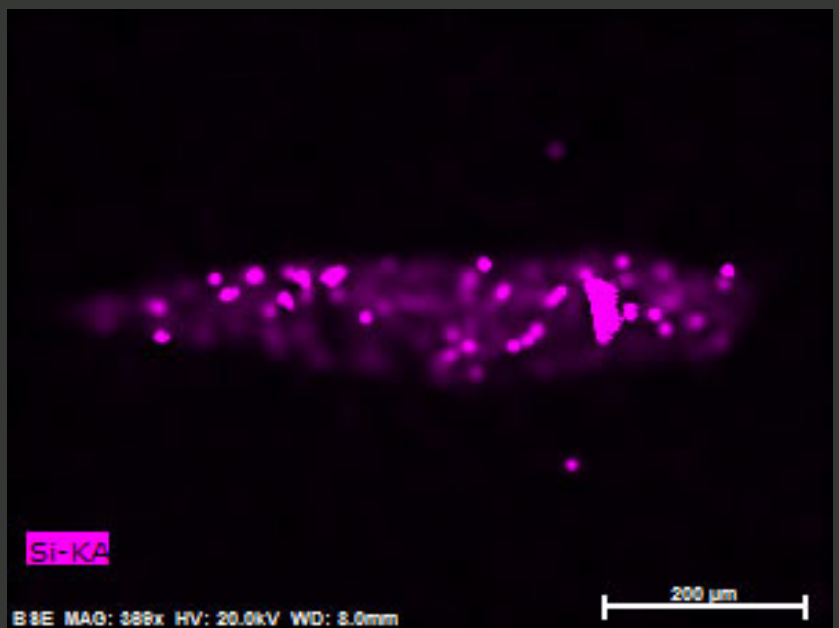
Pb

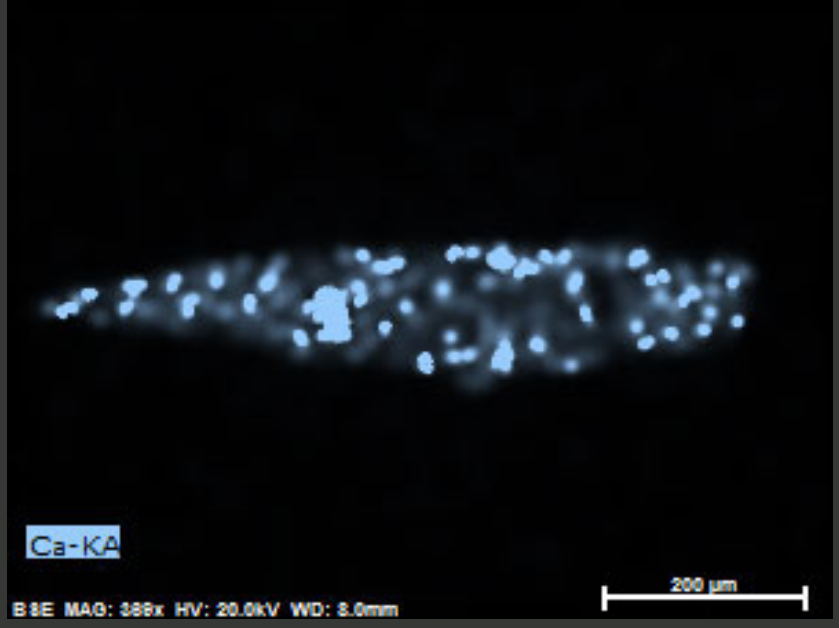


MAG: 282x
HV: 20 kV
WD: 8.7 mm
Scale bar: 200 µm

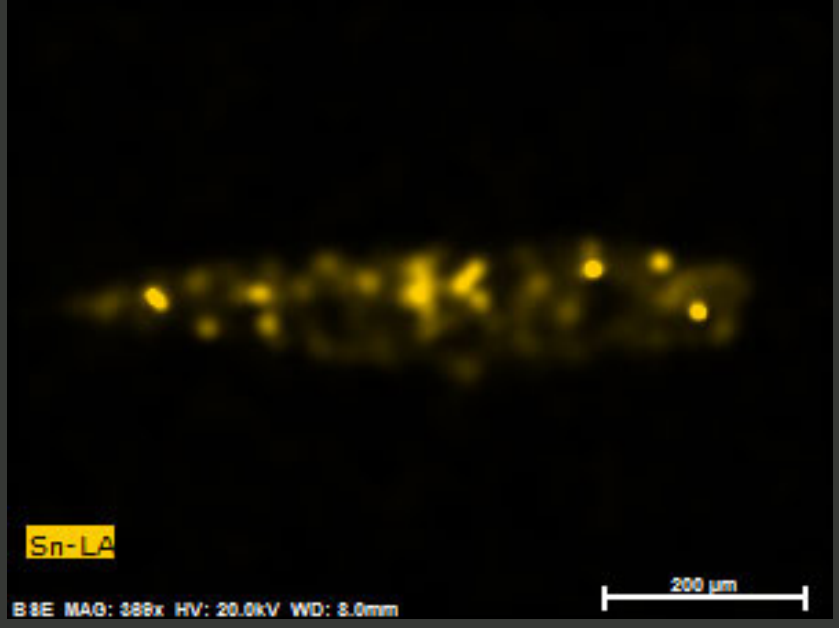

Mg-K
200 µm
B 8E MAG: 388x HV: 20.0kV WD: 8.0mm

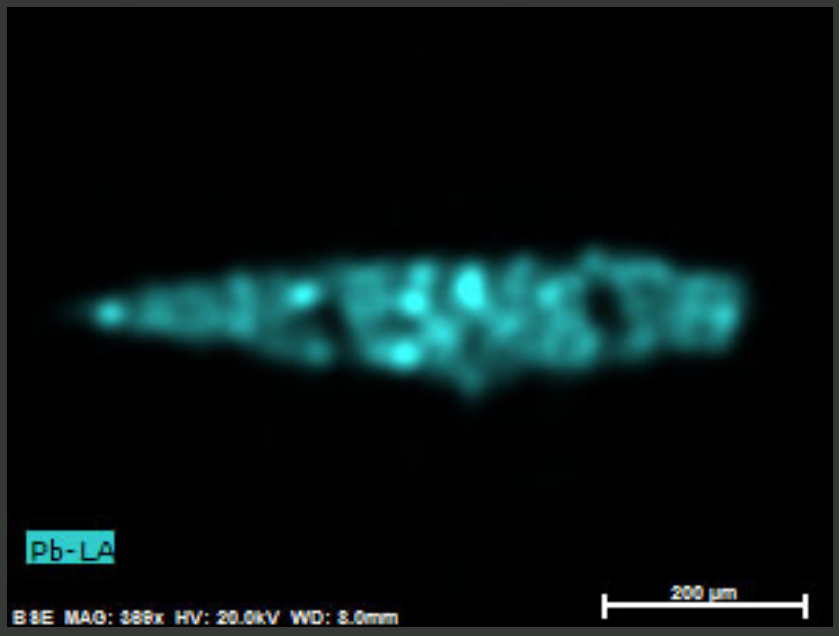

Al-K
200 µm
B 8E MAG: 388x HV: 20.0kV WD: 8.0mm


Si-KA
200 µm
B 8E MAG: 388x HV: 20.0kV WD: 8.0mm


Ca-KA
B 8E MAG: 388x HV: 20.0kV WD: 8.0mm
200 µm

Fe-KA
B 8E MAG: 388x HV: 20.0kV WD: 8.0mm
200 µm

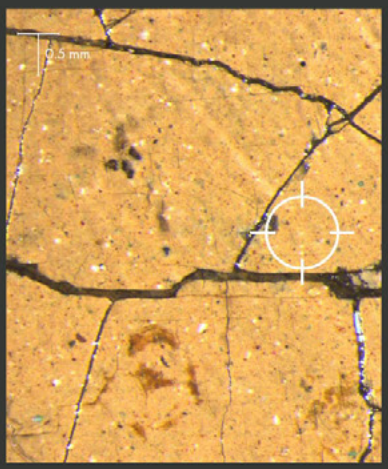

Sn-LA
B 8E MAG: 388x HV: 20.0kV WD: 8.0mm
200 µm


Pb-LA
B 8E MAG: 388x HV: 20.0kV WD: 8.0mm
200 µm

Cross Section 12 (CS12)

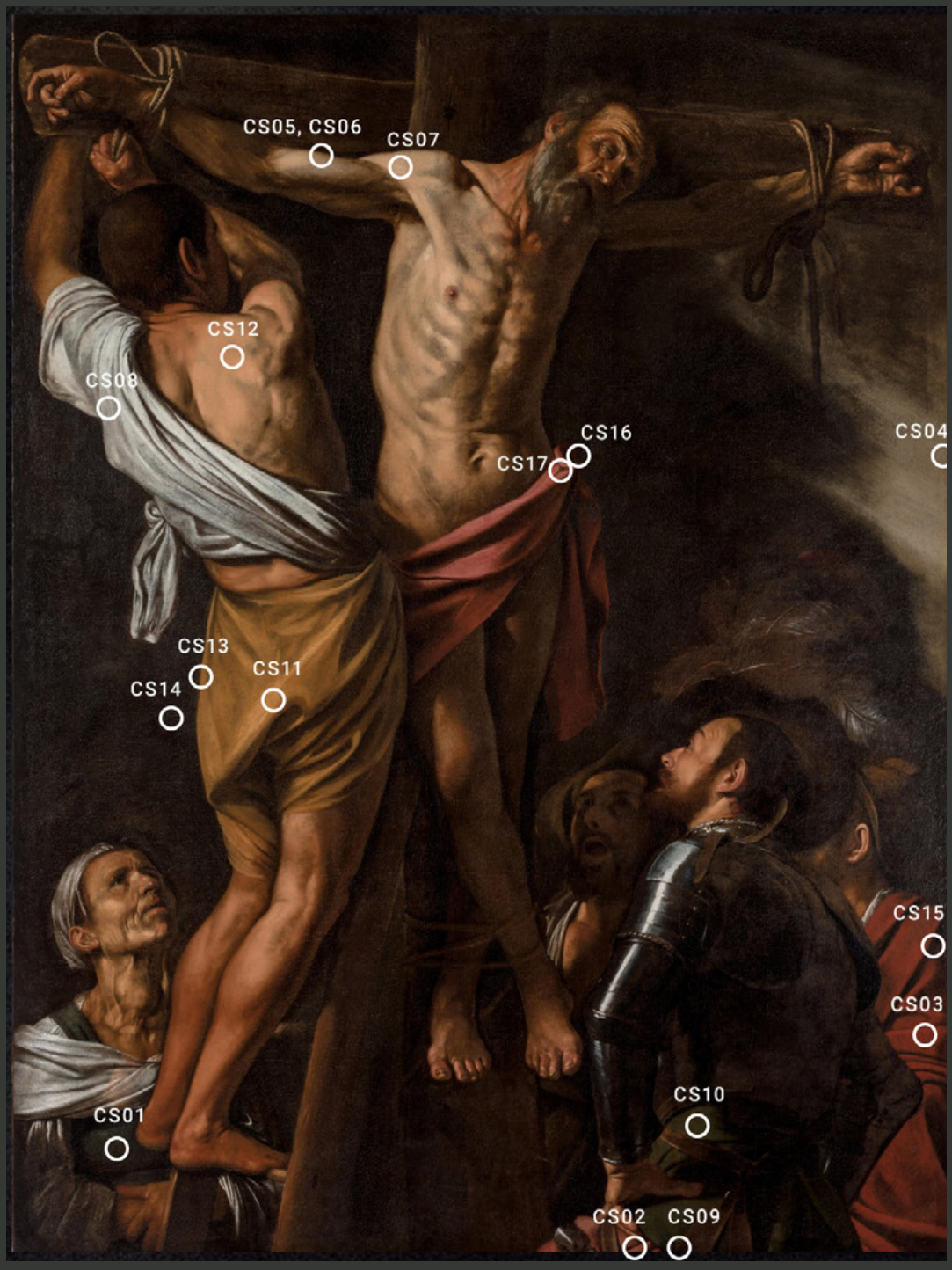
Location: Scapula of the executioner on the ladder

Sample 12 was taken after treatment to identify pigments used in the flesh tones of the executioner on the ladder and to see if these pigments were similar to those used in Saint Andrew's flesh tones.



CROSS SECTIONS

RAMAN SPECTROSCOPY


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

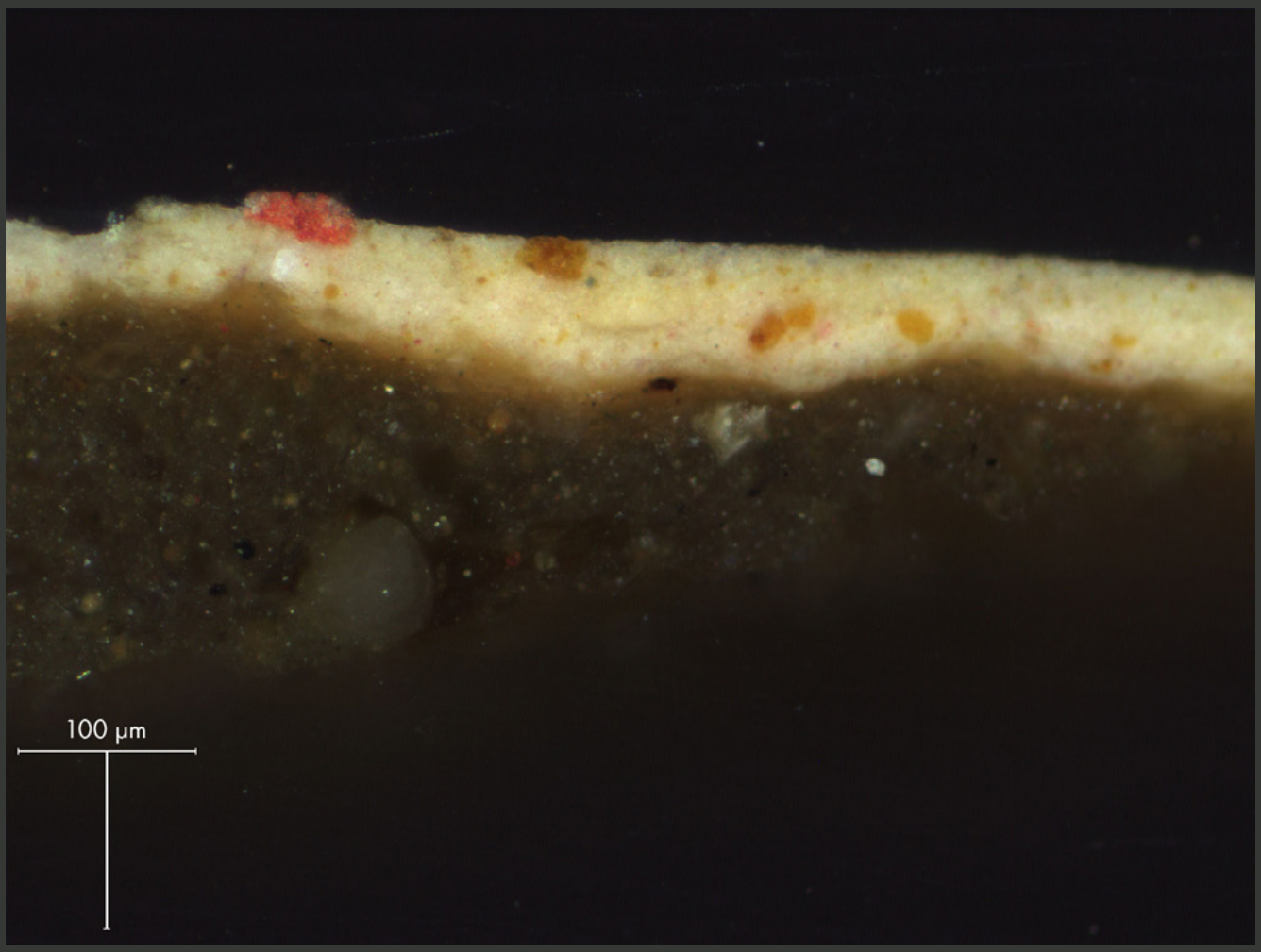
Cross Section 12 (CS12)

Location: Scapula of the executioner on the ladder

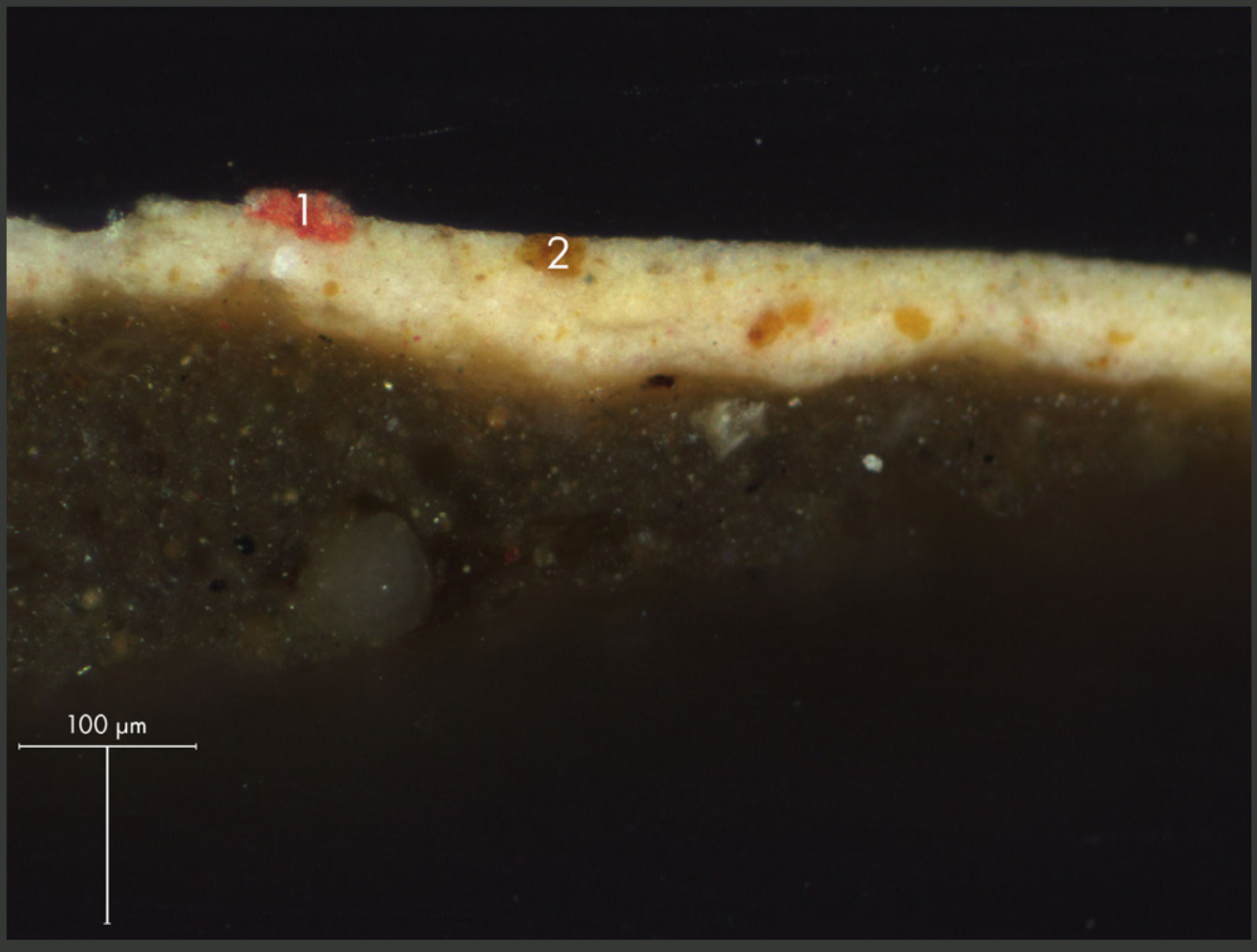
Sample 12 was taken after treatment to identify pigments used in the flesh tones of the executioner on the ladder and to see if these pigments were similar to those used in Saint Andrew's flesh tones.

CROSS SECTIONS

Normal Light Overlay



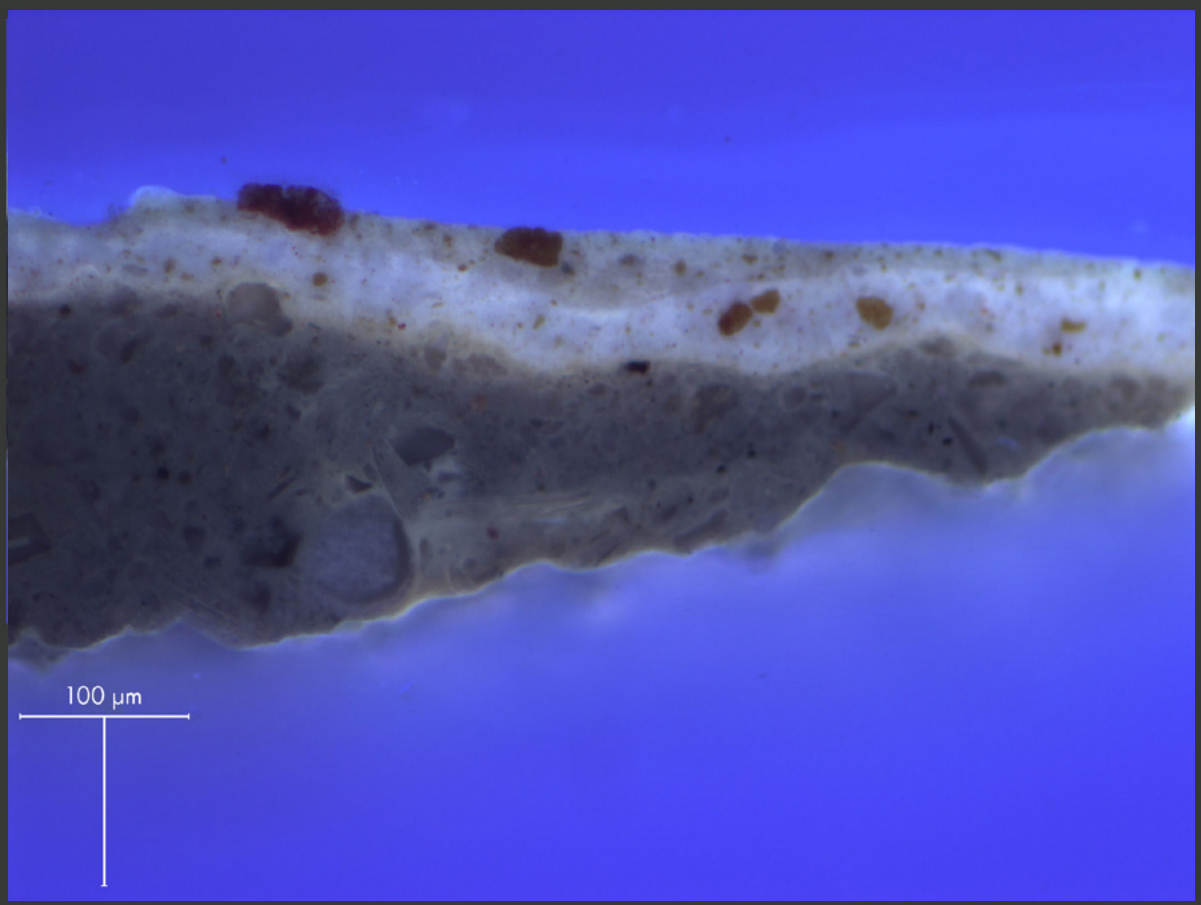
(1) Hematite
(2) Yellow ochre


1
2
100 µm

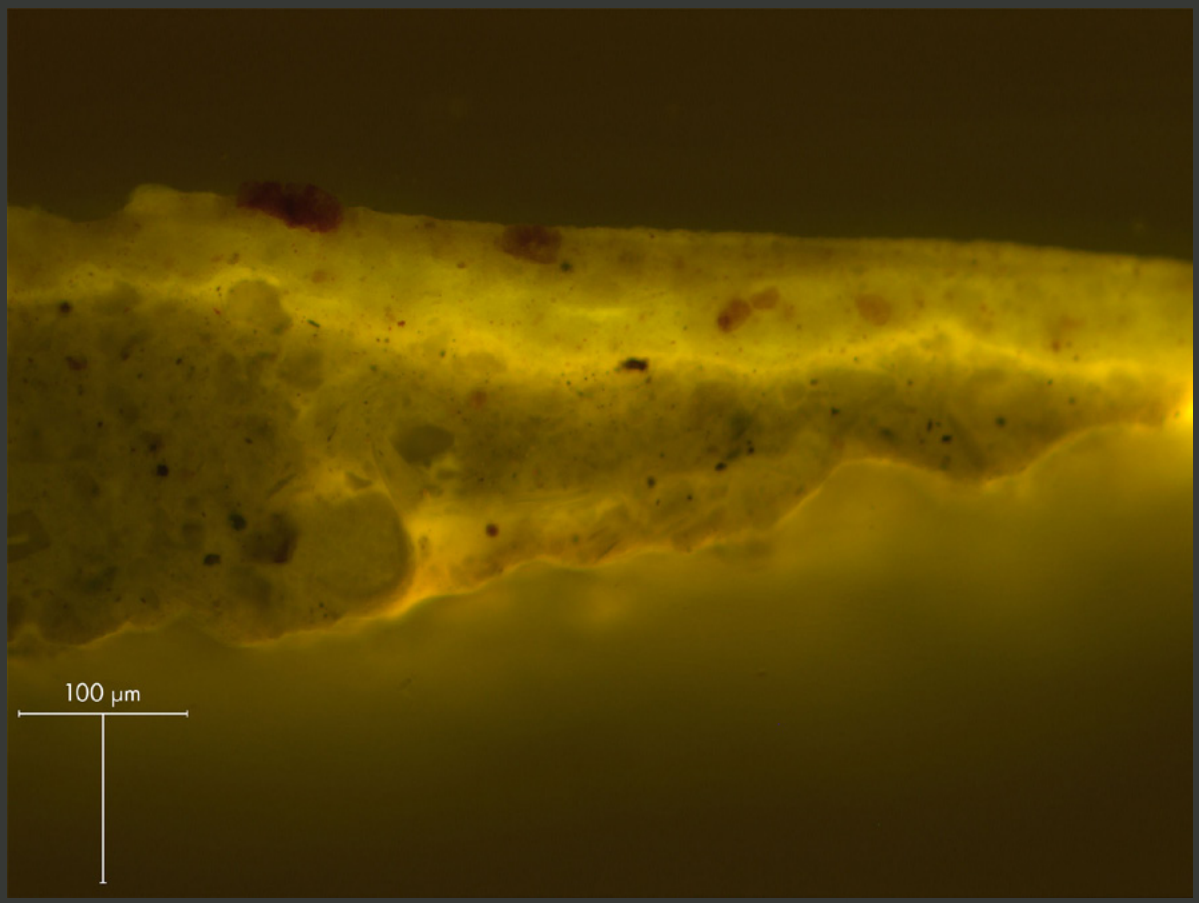
Cross Section 12 (CS12)

Location: Scapula of the executioner on the ladder

Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm)



Excitation: blue (450–490 nm)
Emission: green (λ_{em} > 515 nm)



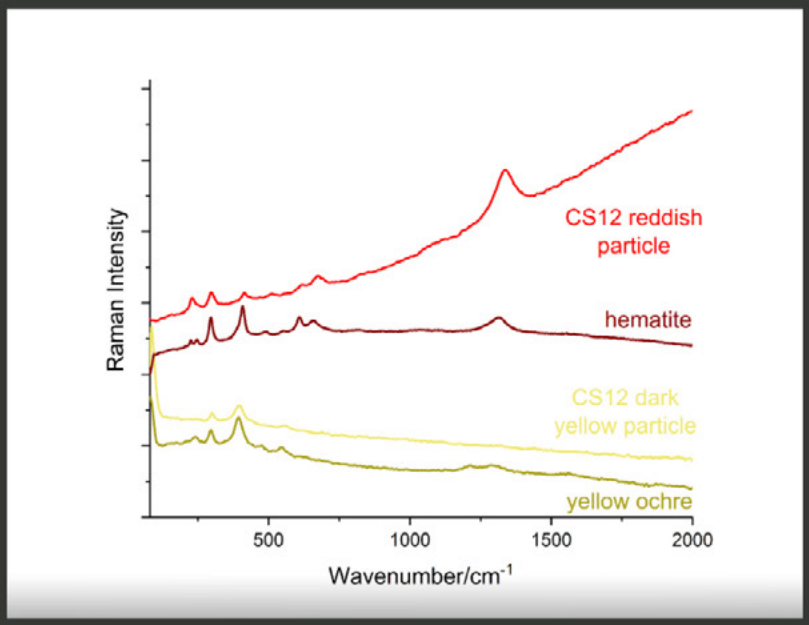
Two thin layers of flesh-colored paint have been applied over the dark brown upper ground layer. Both paint layers are similar in thickness; however, the lower paint is slightly lighter in value and has a lighter fluorescence under both UV and blue excitation. Both paint layers are predominantly composed of lead white with earth pigments, including red ochre (hematite) and yellow ochre. Raman spectroscopy confirmed the red particle (1) as hematite and the yellow particle (2) as yellow ochre. Only the upper ground and a portion of the lower ground are present in this sample. SEM-EDS was not conducted on this sample, because molecular analysis was able to identify the pigments in the paint layer.

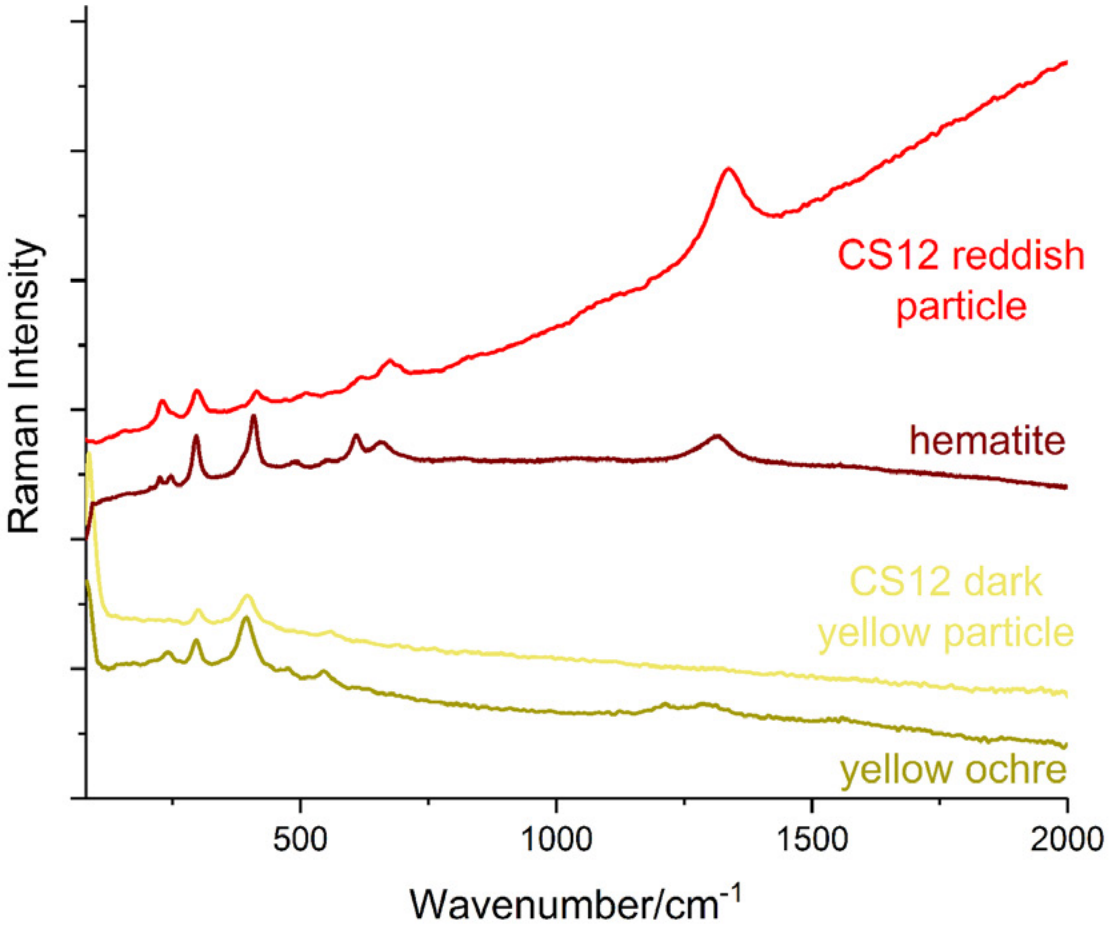
Cross Section 12 (CS12)

Location: Scapula of the executioner on the ladder

Two thin layers of flesh-colored paint have been applied over the dark brown upper ground layer. Both paint layers are similar in thickness; however, the lower paint is slightly lighter in value and has a lighter fluorescence under both UV and blue excitation. Both paint layers are predominantly composed of lead white with earth pigments, including red ochre (hematite) and yellow ochre. Raman spectroscopy confirmed the red particle (1) as hematite and the yellow particle (2) as yellow ochre. Only the upper ground and a portion of the lower ground are present in this sample. SEM-EDS was not conducted on this sample, because molecular analysis was able to identify the pigments in the paint layer.

RAMAN SPECTROSCOPY

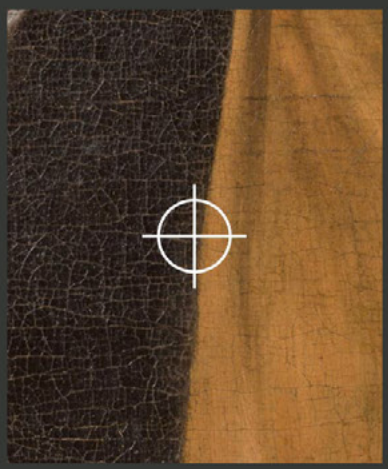


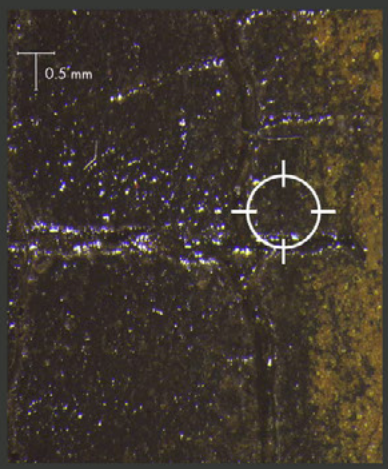

Raman Intensity
CS12 reddish particle
hematite
CS12 dark yellow particle
yellow ochre
500
1000
1500
2000
Wavenumber/cm-1

Cross Section 13 (CS13)

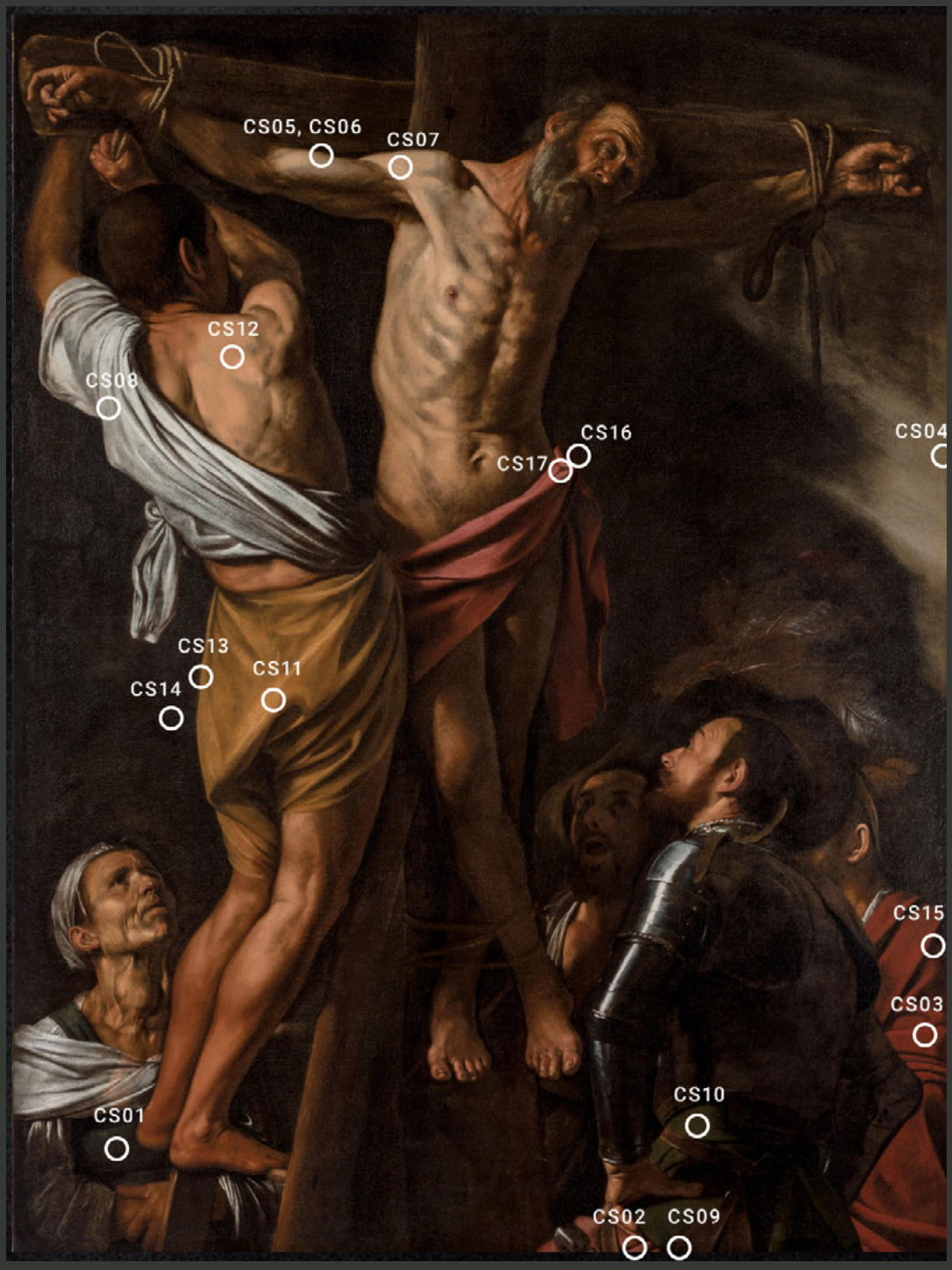
Location: Background area close to the executioner's yellow trousers

Sample 13 was taken after treatment to identify the pigments and structure of the paint used in the background. Because only a small portion of the paint layer was retained during sampling, the analysis for the background focused on cross section 14.





CROSS SECTIONS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

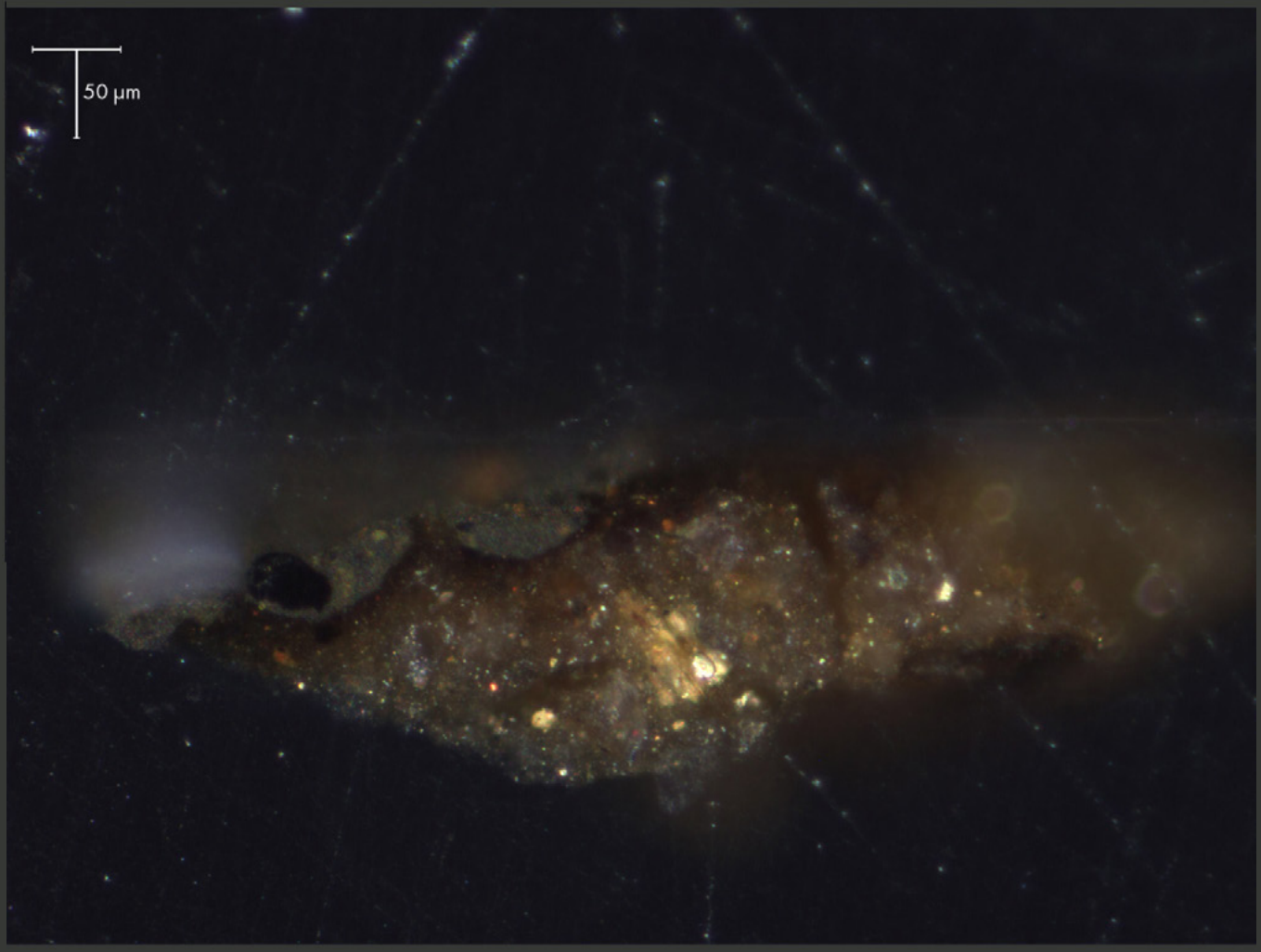
Cross Section 13 (CS13)

Location: Background area close to the executioner's yellow trousers

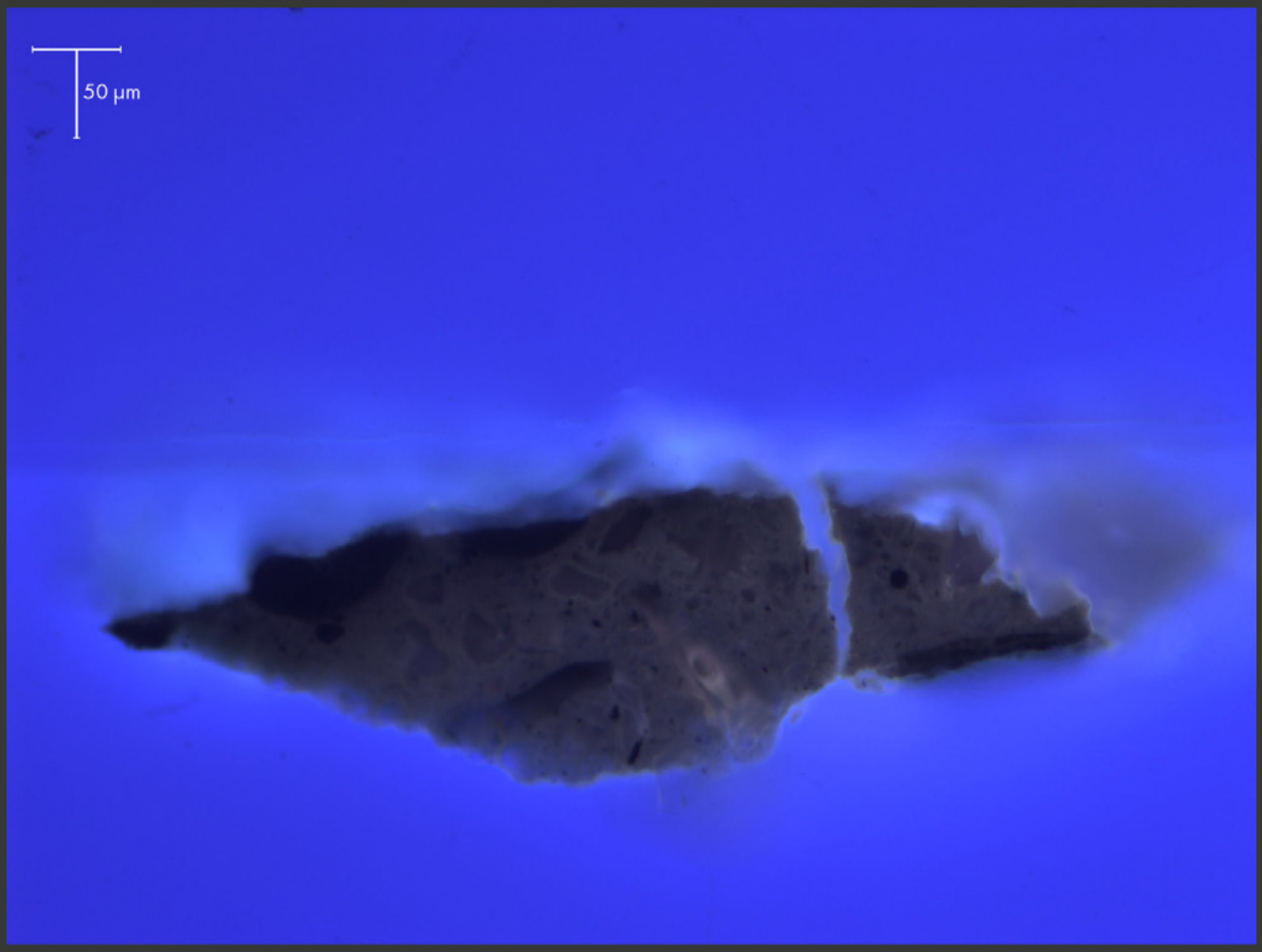
Sample 13 was taken after treatment to identify the pigments and structure of the paint used in the background. Because only a small portion of the paint layer was retained during sampling, the analysis for the background focused on cross section 14.

CROSS SECTIONS

Normal Light



Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm)

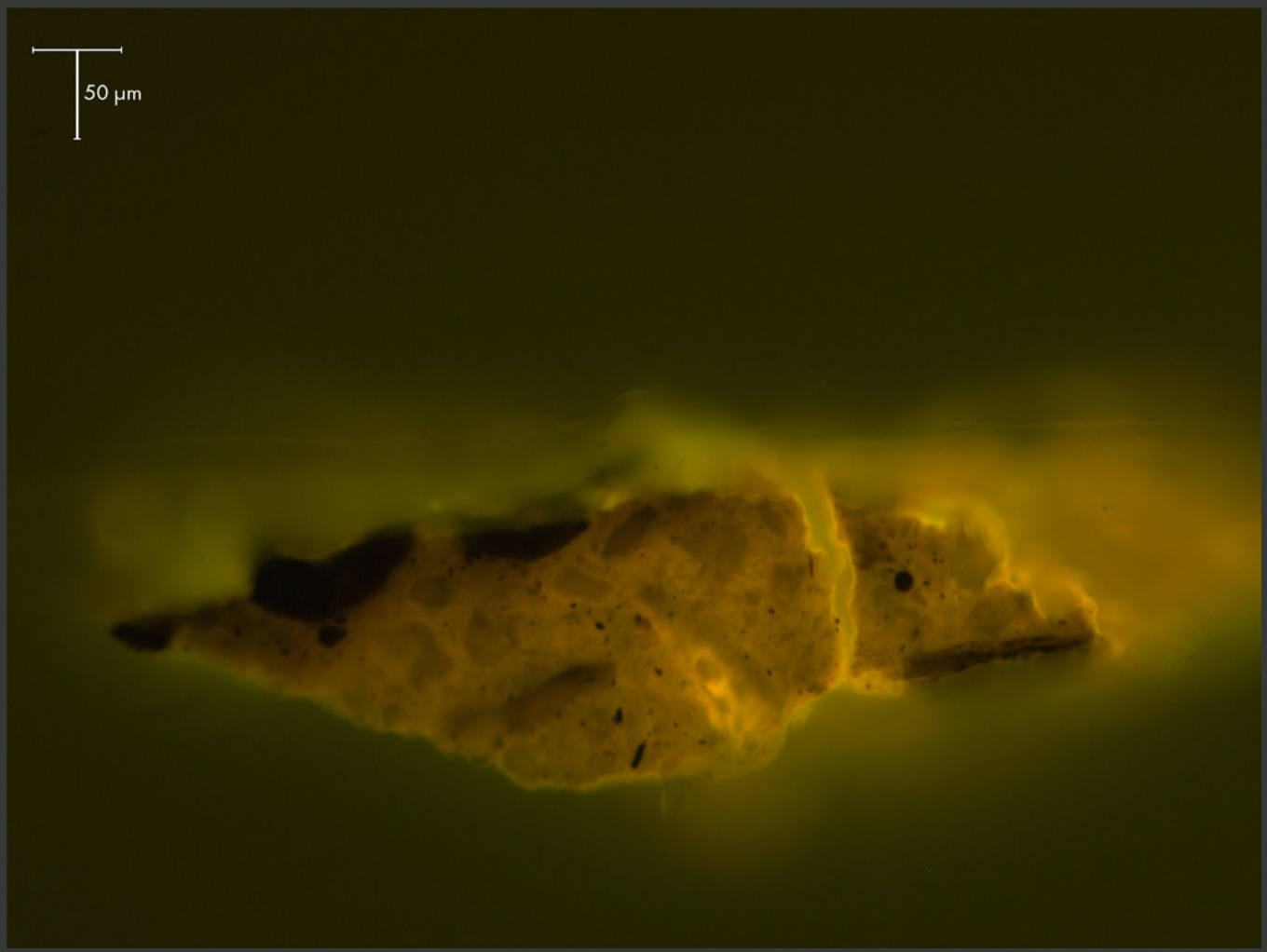


Cross Section 13 (CS13)

Location: Background area close to the executioner's yellow trousers

Sample 13 was taken after treatment to identify the pigments and structure of the paint used in the background. Because only a small portion of the paint layer was retained during sampling, the analysis for the background focused on cross section 14.

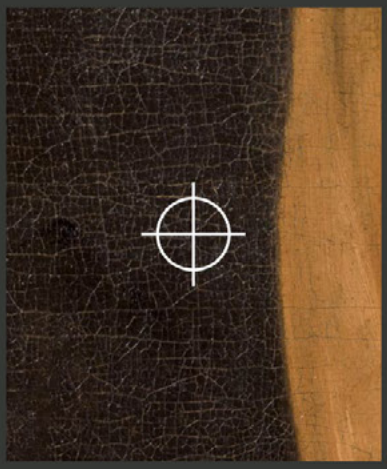
Excitation: blue (450–490 nm)
Emission: green (λ_{em} > 515 nm)

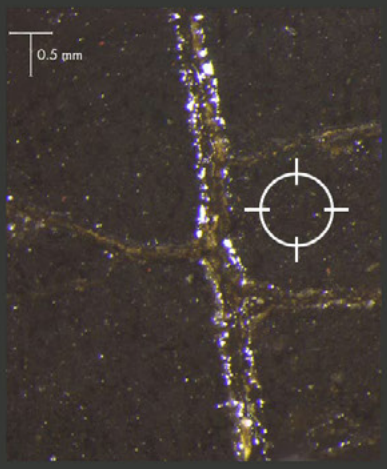


Cross Section 14 (CS14)

Location: Background area to the left of executioner standing on the ladder

Sample 14 was taken to identify the pigments and structure of the dark umber-colored paint in the background.



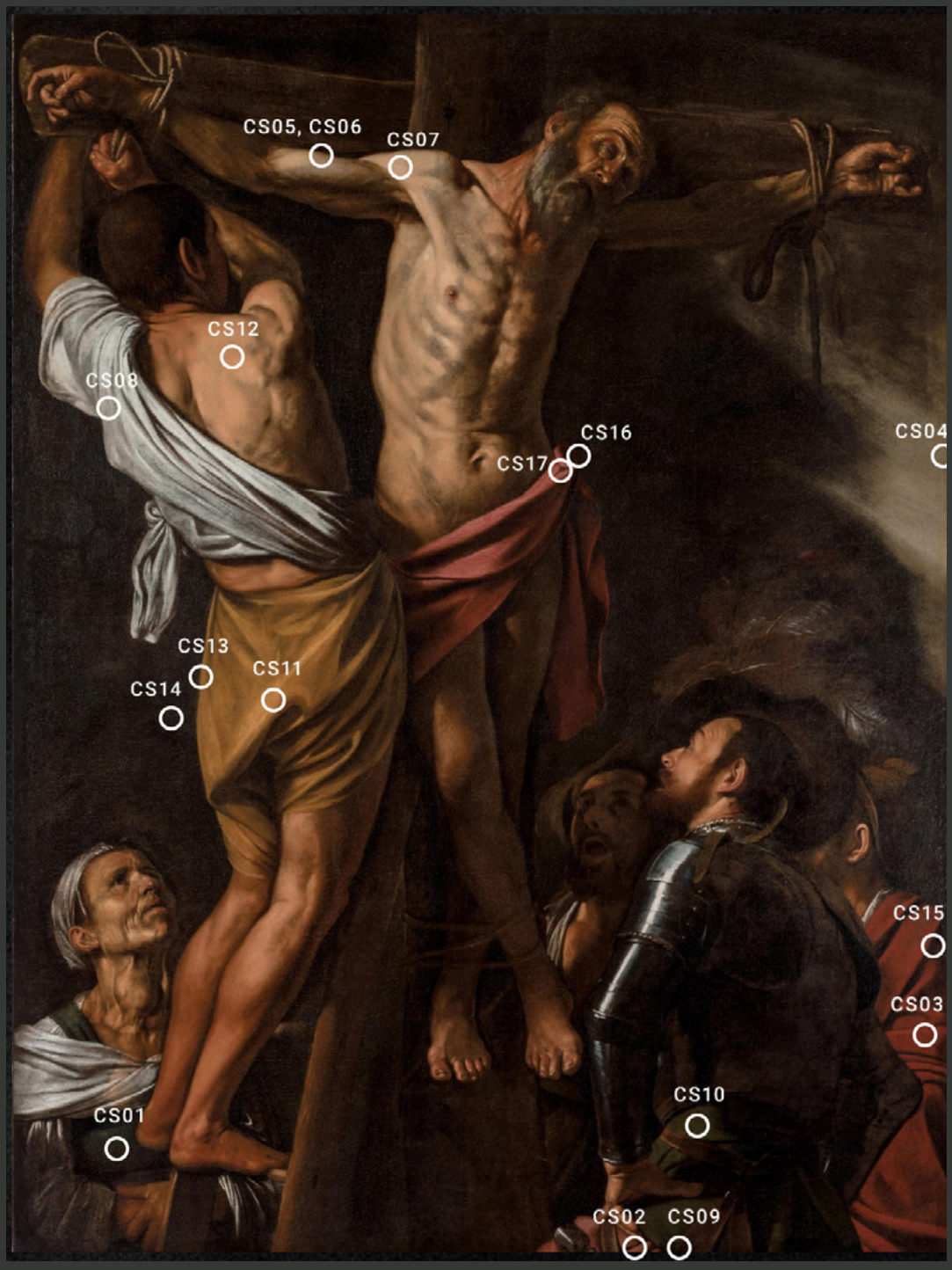


CROSS SECTIONS

GROUND LAYERS

PAINT LAYERS

SEM-EDS MAPS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

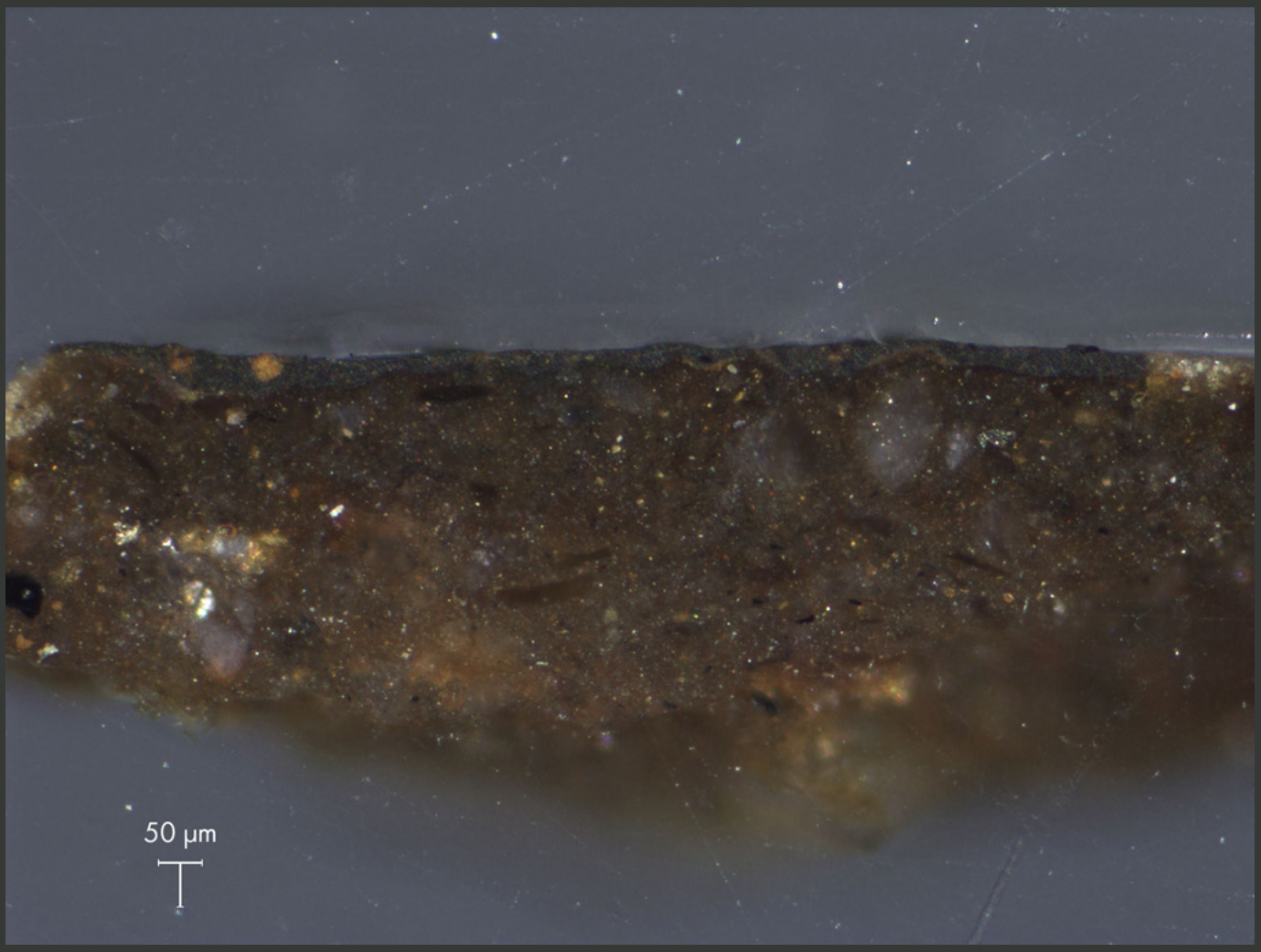
Cross Section 14 (CS14)

Location: Background area to the left of executioner standing on the ladder

Sample 14 was taken to identify the pigments and structure of the dark umber-colored paint in the background.

CROSS SECTIONS

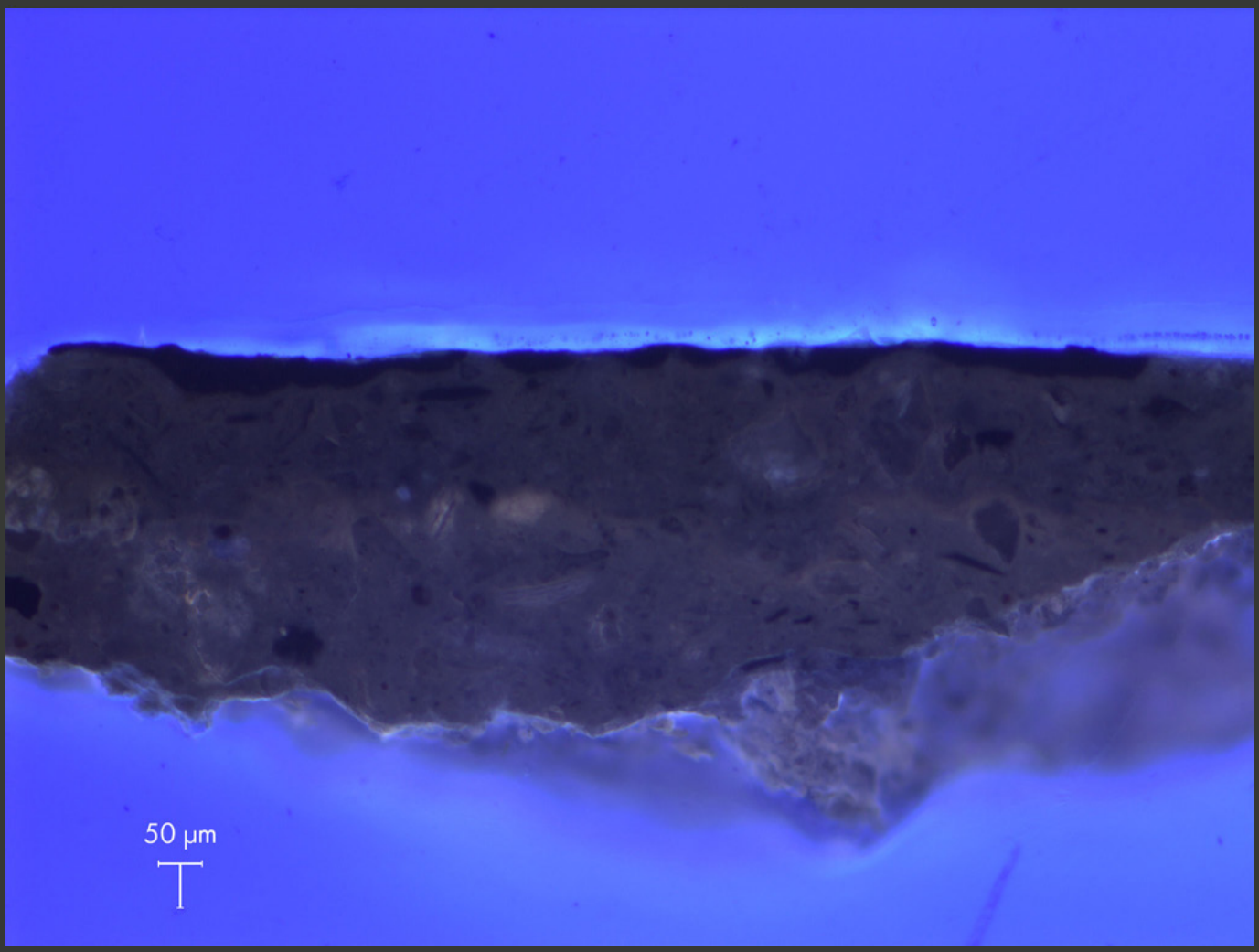
Normal Light



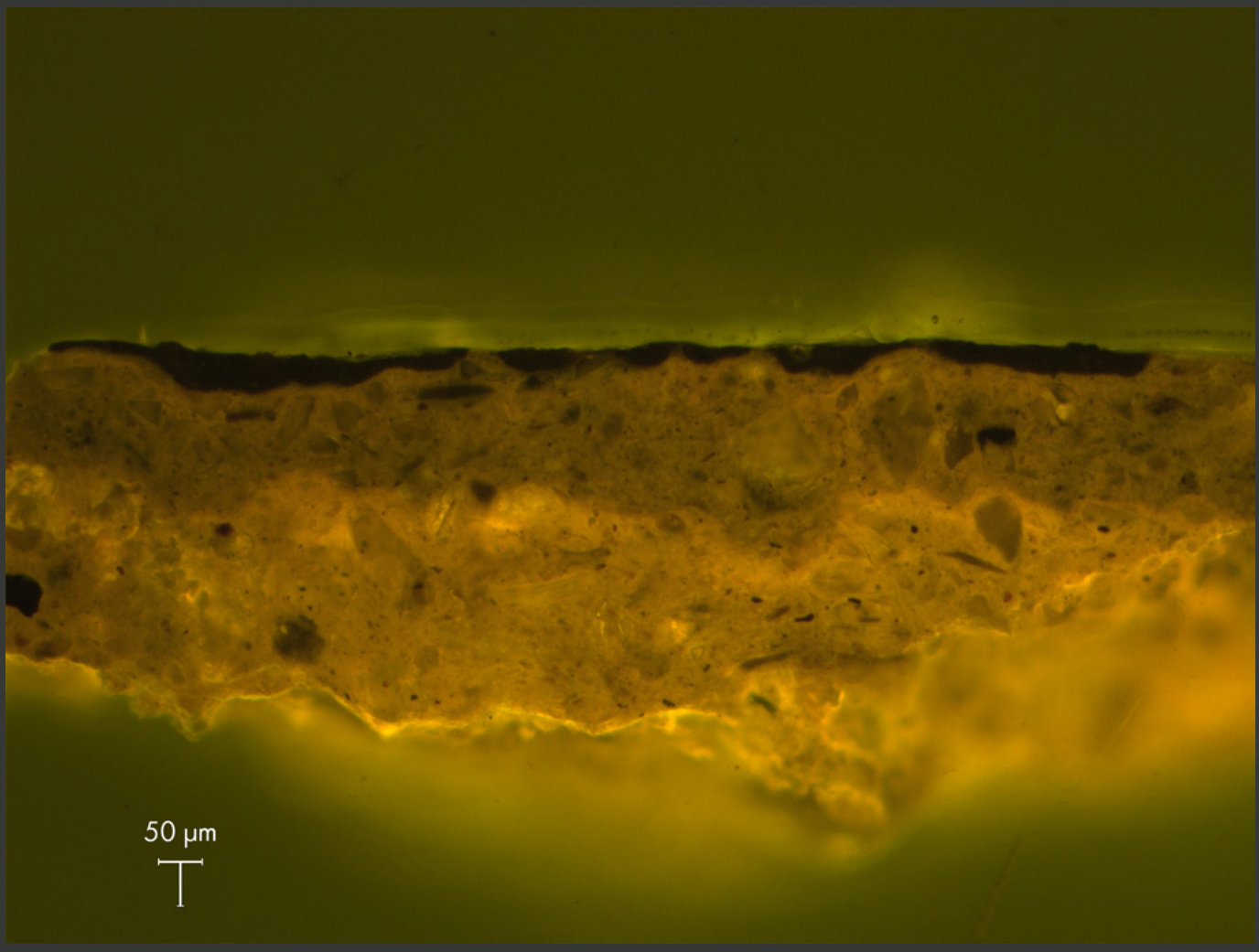
Cross Section 14 (CS14)

Location: Background area to the left of executioner standing on the lad

Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm)



Excitation: blue (450–490 nm)
Emission: green (λ_{em} > 515 nm)



Cross Section 14 (CS14)

Location: Background area to the left of executioner standing on the ladc

GROUND LAYERS

From the elemental maps, both the upper and lower ground layers have an even distribution of aluminum, silicon, potassium, and calcium, with some scattered particles containing titanium, magnesium, and sodium.

PAINT LAYERS

According to the EDS maps, this thinly applied paint layer, measuring only about 20–30 microns, is entirely composed of iron and manganese, indicative of an umber pigment.

SEM-EDS MAPS

BSE

Na

Mg

Al

Si

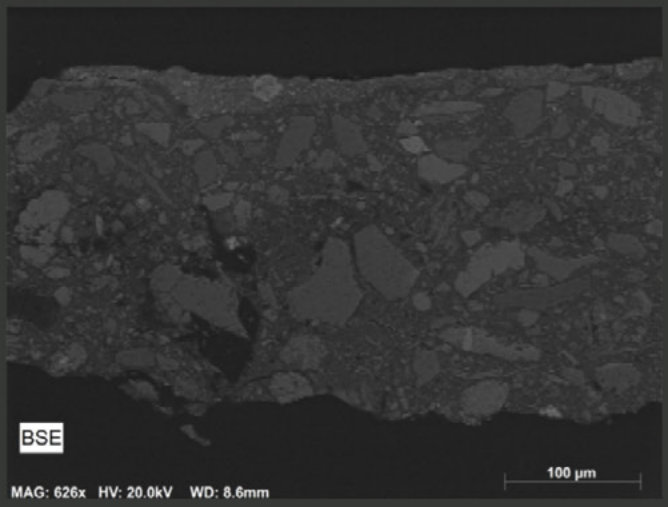
K

Ca

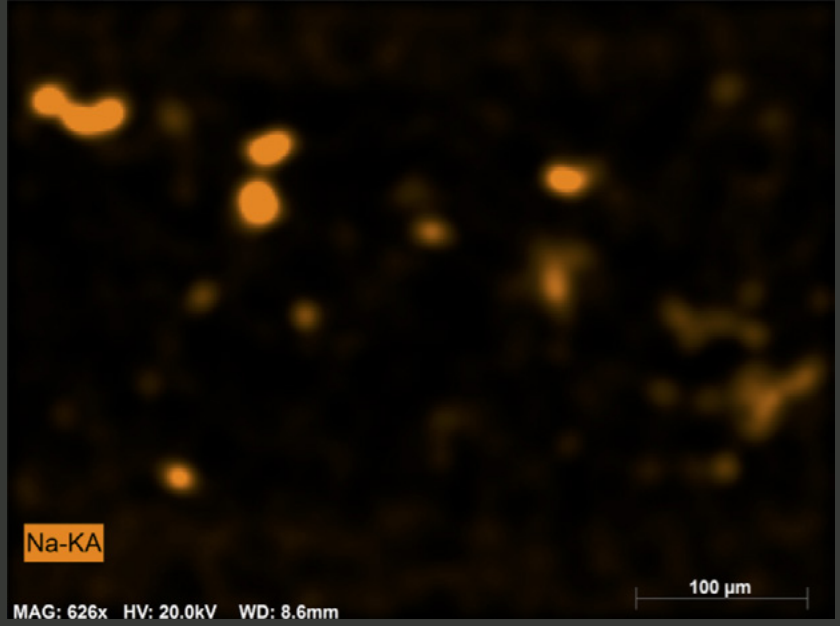
Ti

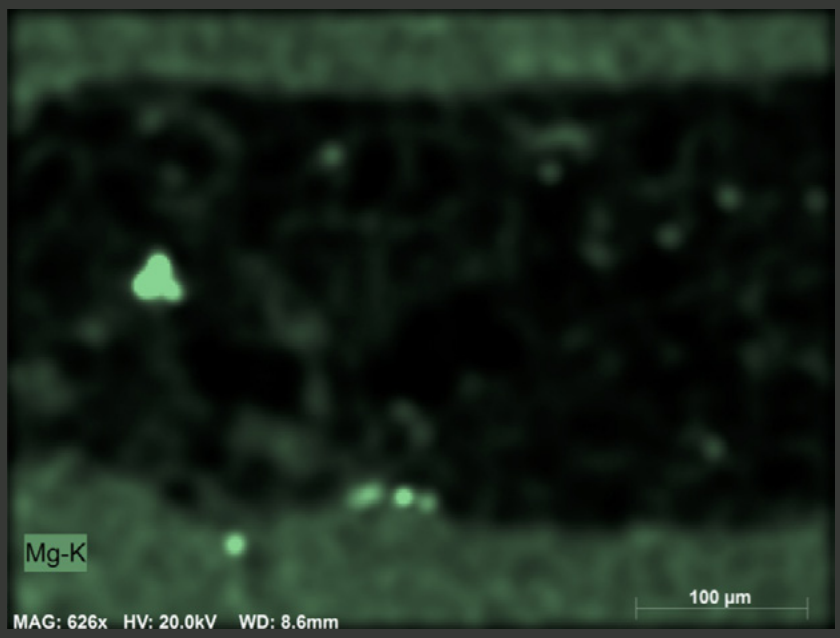
Mn

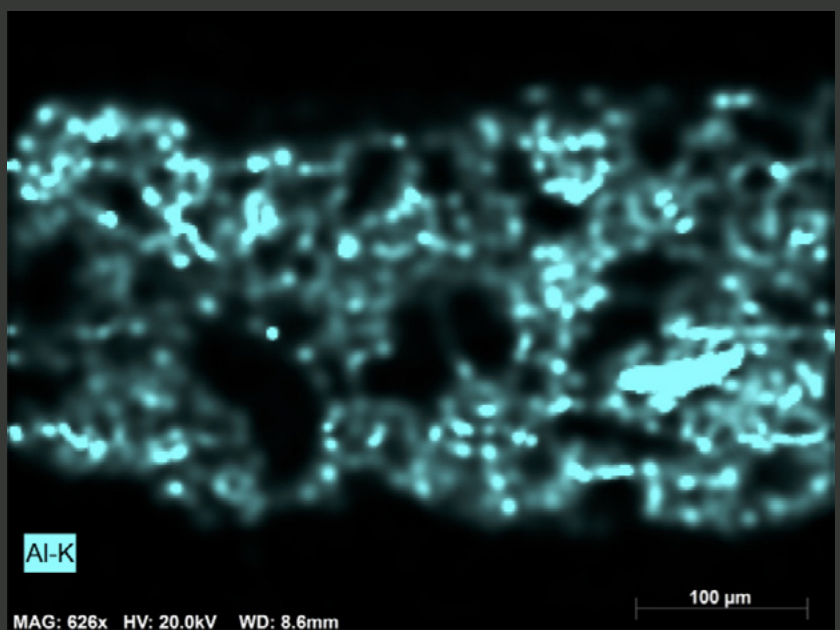
Fe

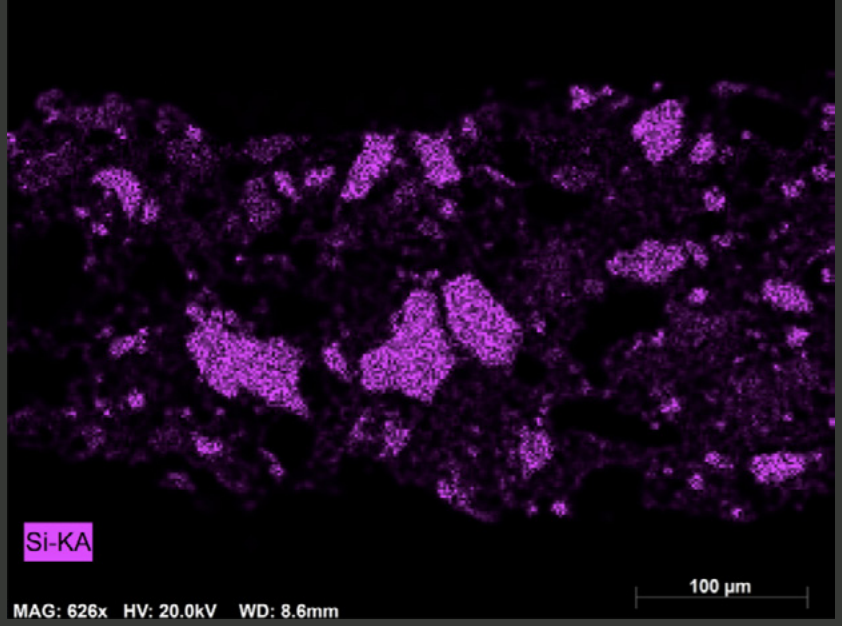


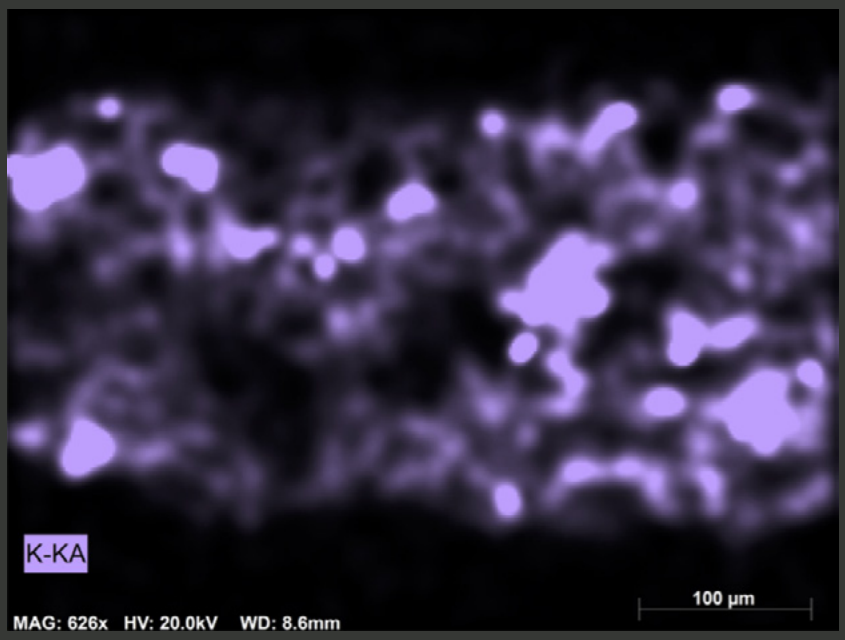
MAG: 626x
HV: 20 kV
WD: 8.6 mm
Scale bar: 100 µm

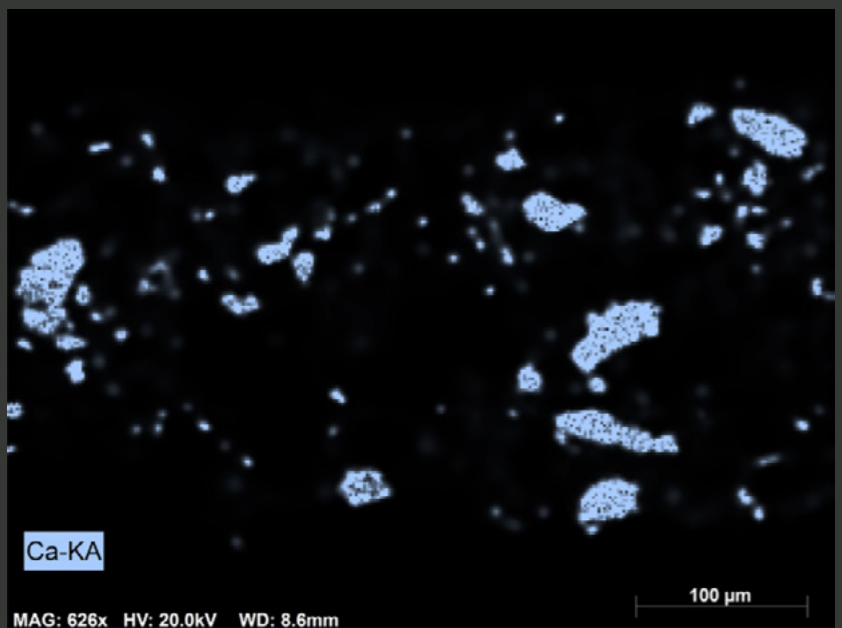

Na-KA
100 µm
MAG: 626x HV: 20.0kV WD: 8.6mm

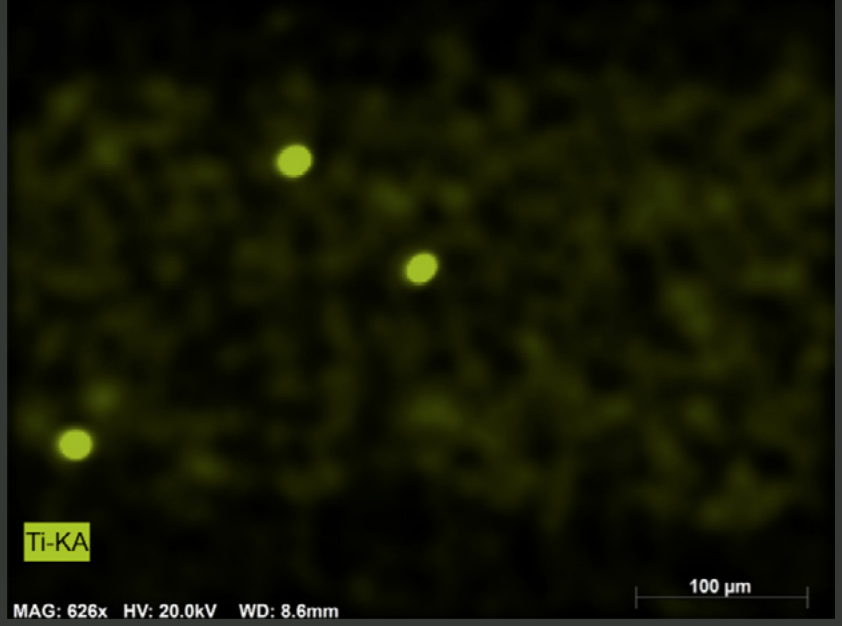

Mg-K
100 µm
MAG: 626x HV: 20.0kV WD: 8.6mm

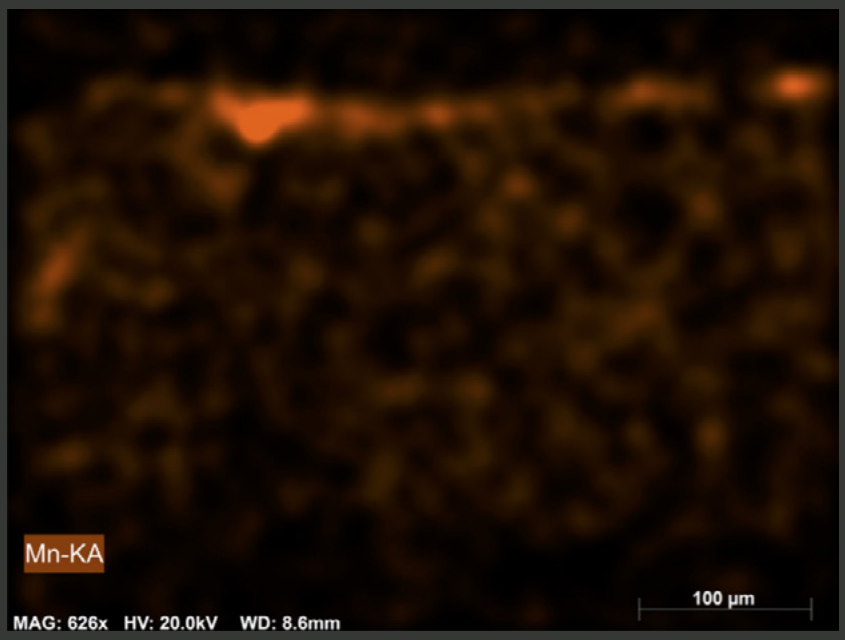

Al-K
100 µm
MAG: 626x HV: 20.0kV WD: 8.6mm

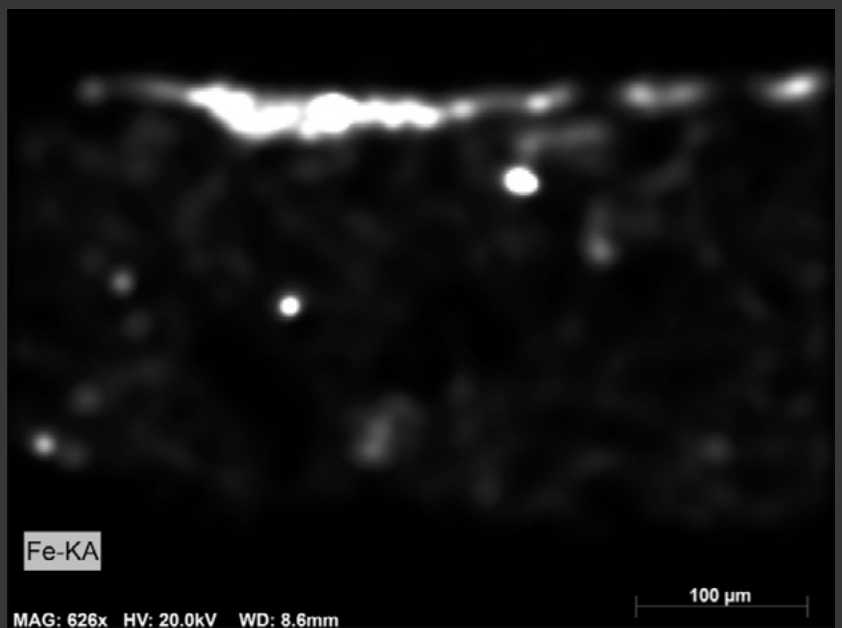

Si-KA
100 µm
MAG: 626x HV: 20.0kV WD: 8.6mm


K-KA
100 µm
MAG: 626x HV: 20.0kV WD: 8.6mm


Ca-KA
100 µm
MAG: 626x HV: 20.0kV WD: 8.6mm


Ti-KA
100 µm
MAG: 626x HV: 20.0kV WD: 8.6mm

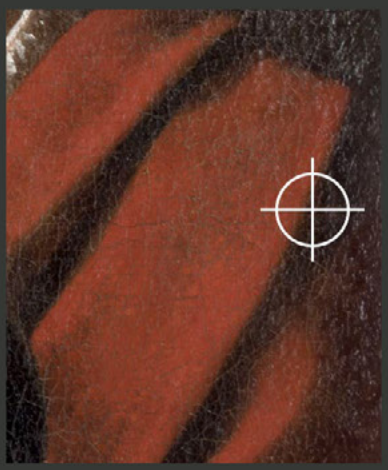

Mn-KA
100 µm
MAG: 626x HV: 20.0kV WD: 8.6mm

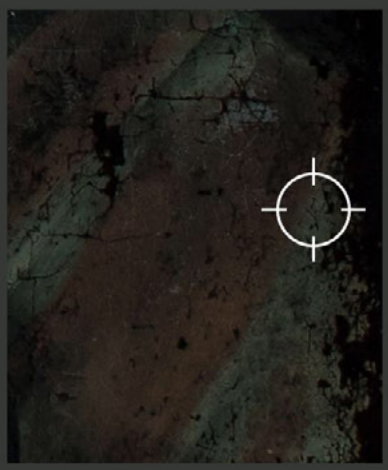

Fe-KA
100 µm
MAG: 626x HV: 20.0kV WD: 8.6mm

Cross Section 15 (CS15)

Location: Dark folds in the red garment of the figure on the right

Sample 15 was taken after treatment to locate the source of the prominent UV-induced fluorescence in the folds of the garment seen in the UV photograph after treatment, and to identify the pigments with SEM-EDS.



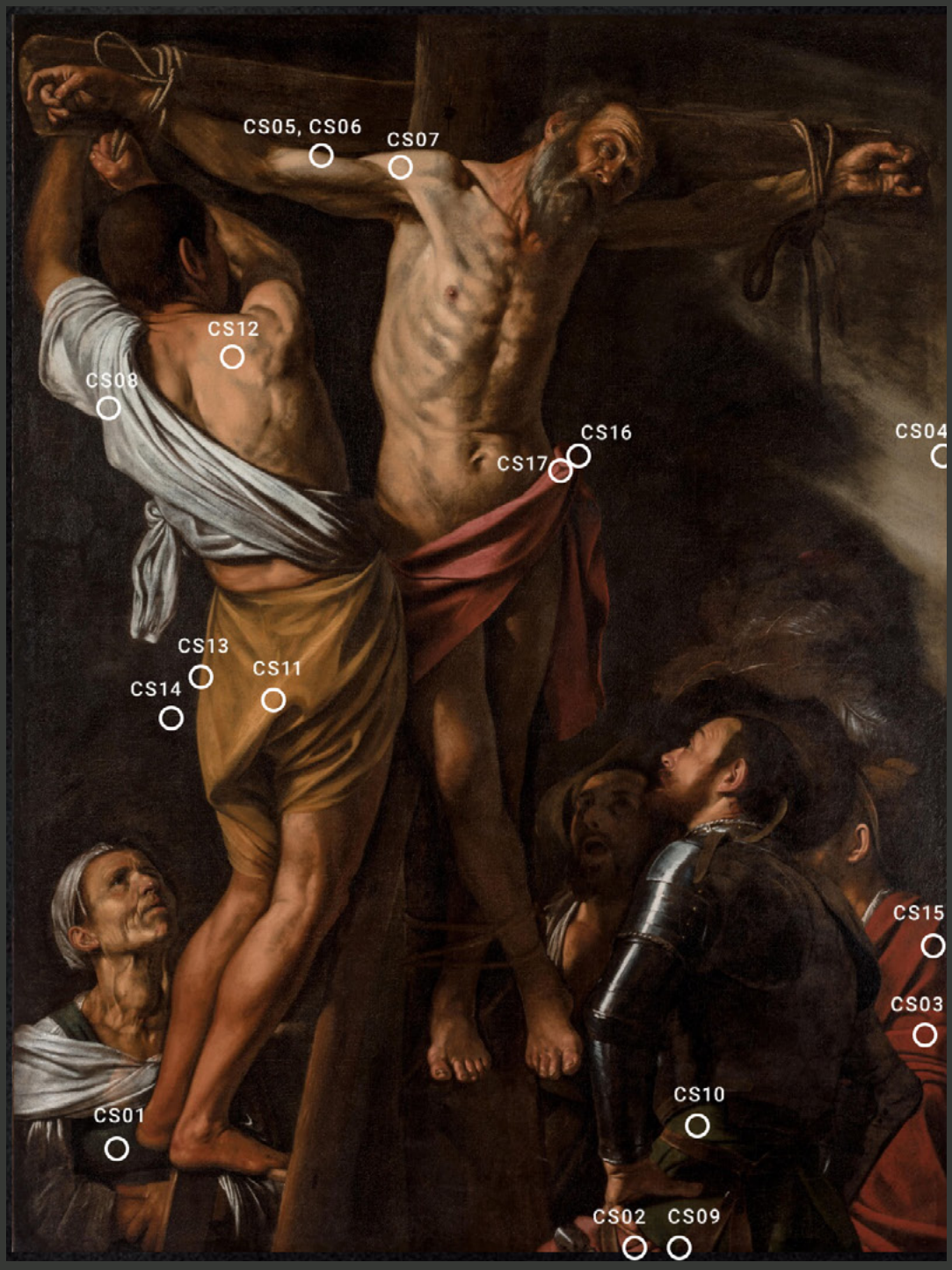


CROSS SECTIONS

GROUND LAYERS

PAINT LAYERS

SEM-EDS MAPS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

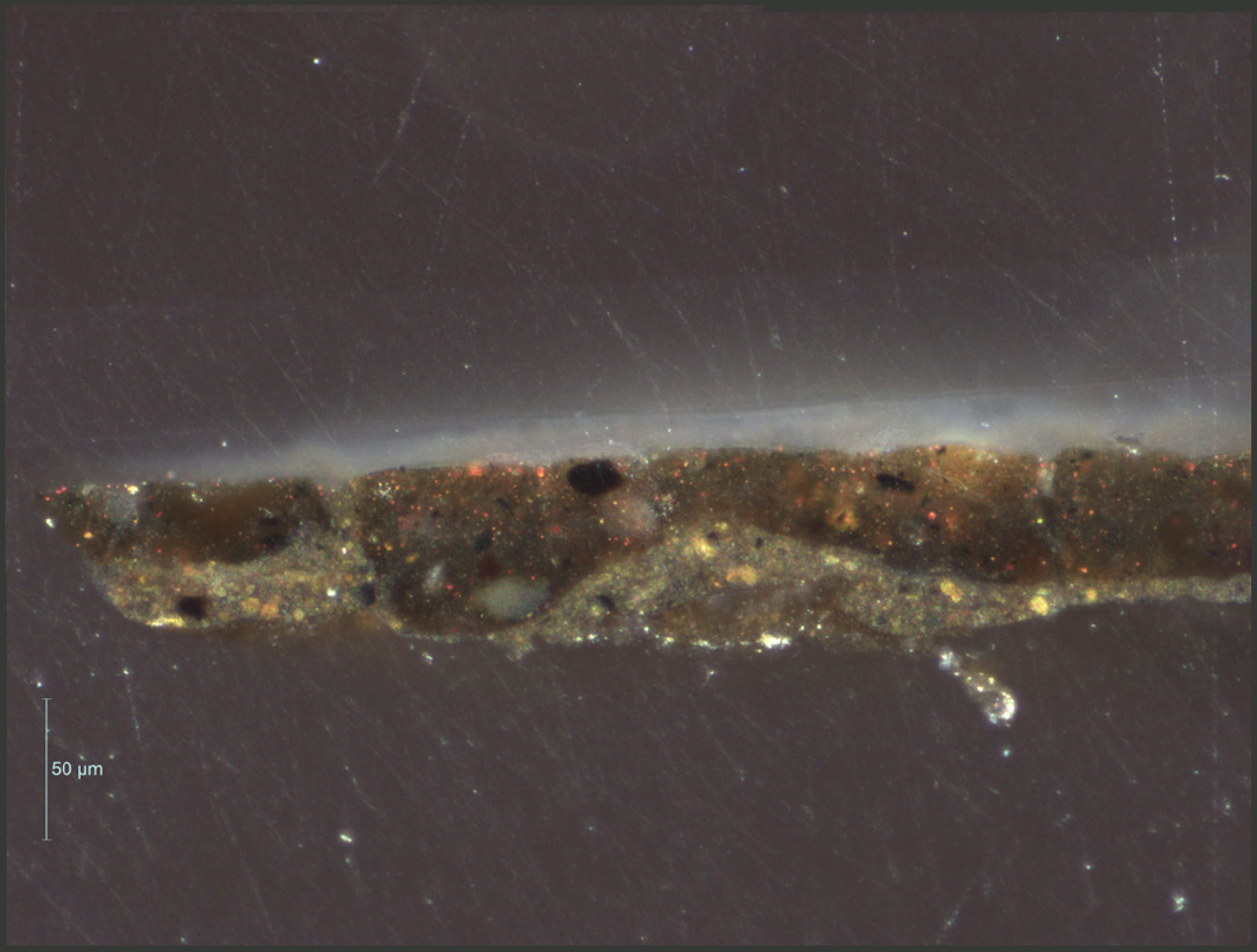
Cross Section 15 (CS15)

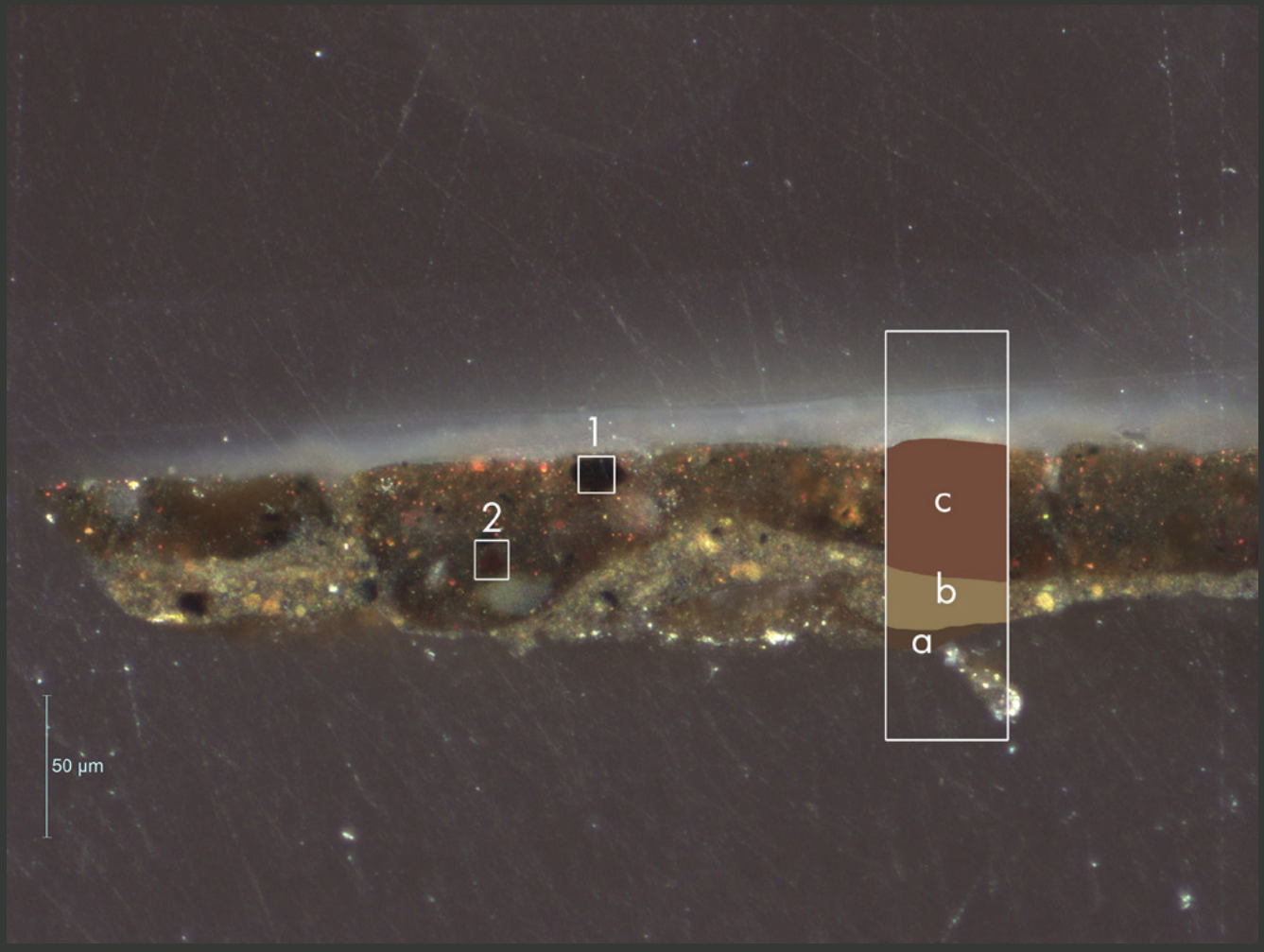
Location: Dark folds in the red garment of the figure on the right

Sample 15 was taken after treatment to locate the source of the prominent UV-induced fluorescence in the folds of the garment seen in the UV photograph after treatment, and to identify the pigments with SEM-EDS.

CROSS SECTIONS

Normal Light Overlay



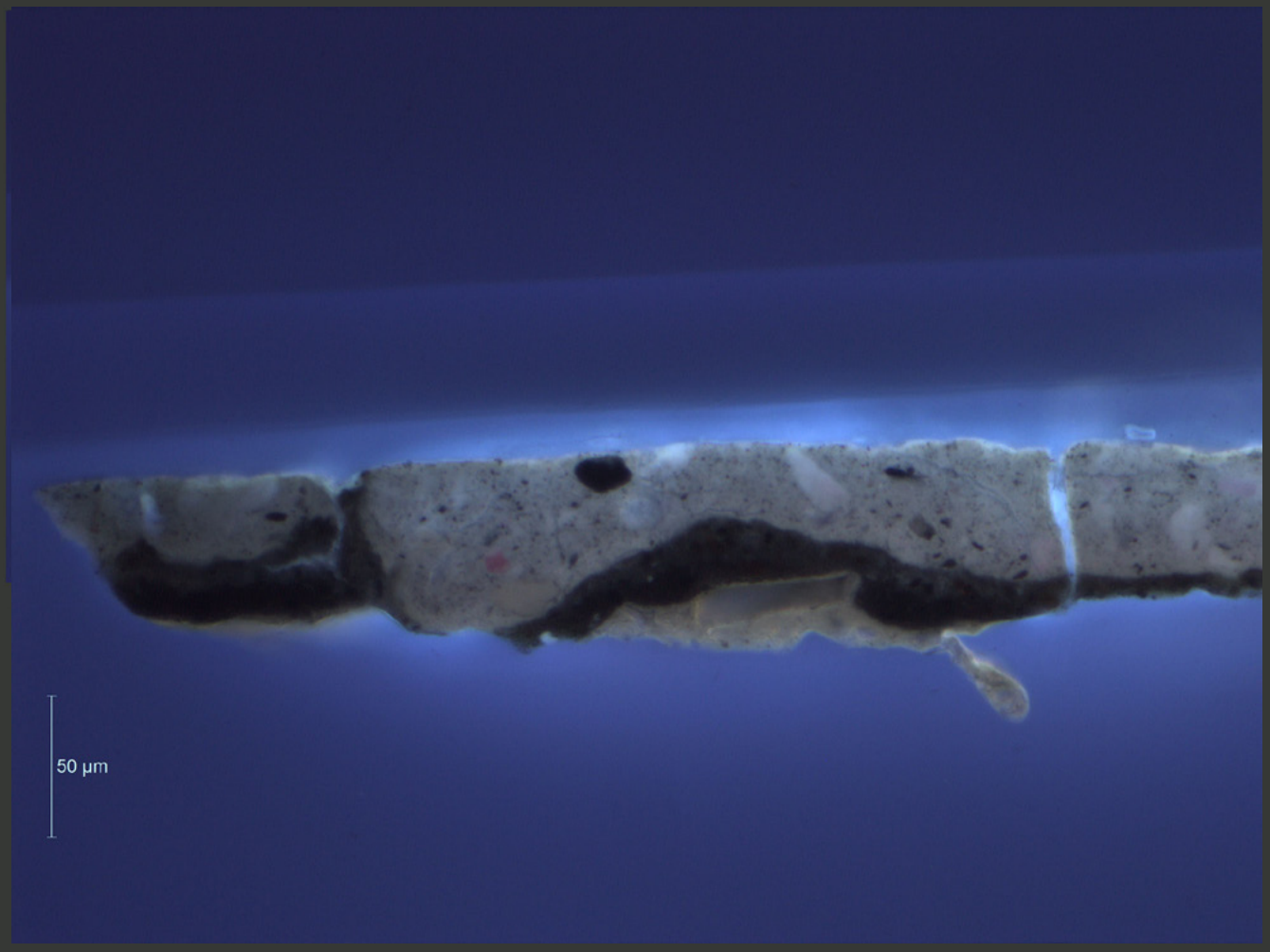

1
2
c
b
a
50 µm

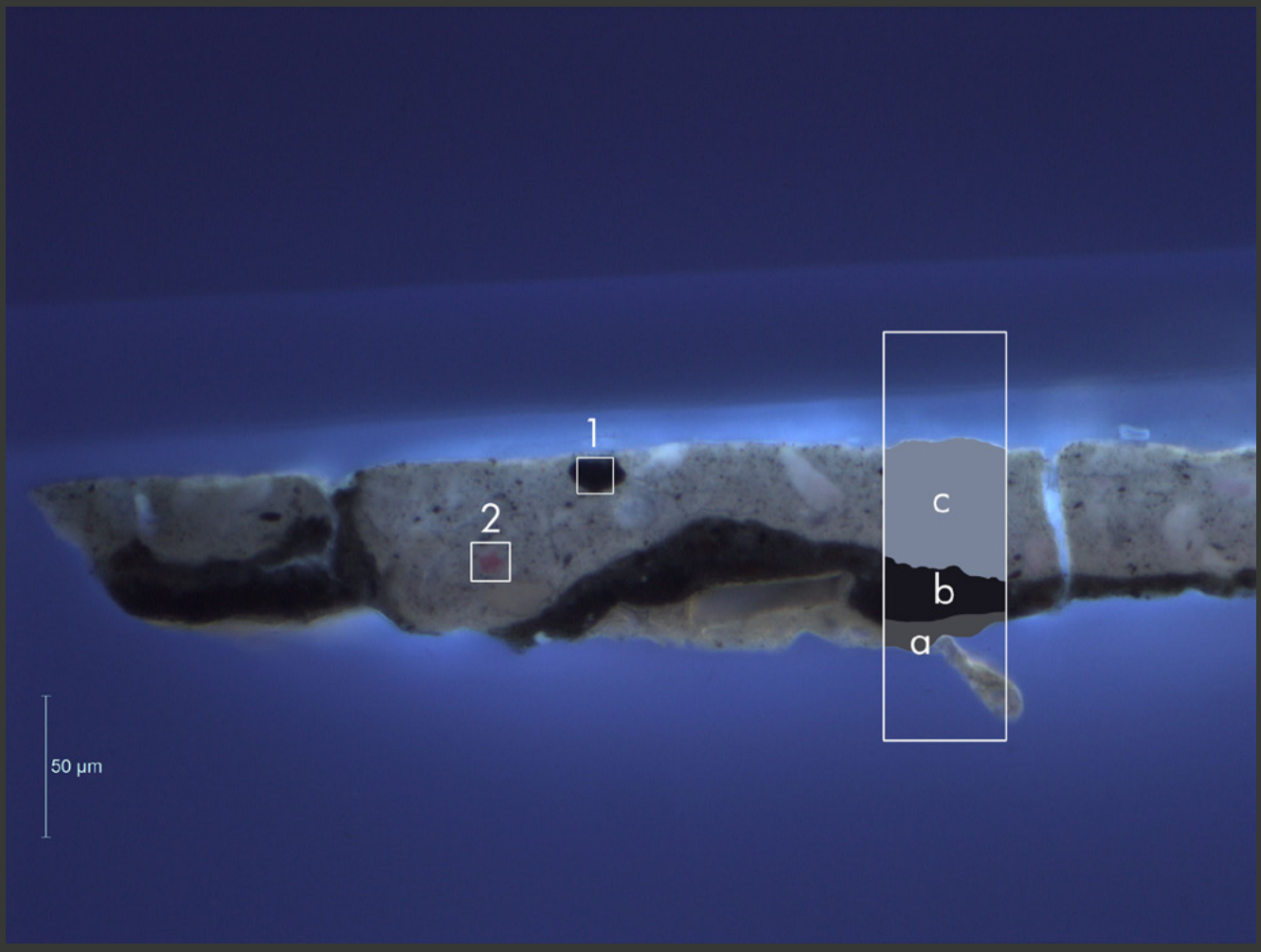
Cross Section 15 (CS15)

Location: Dark folds in the red garment of the figure on the right

Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm)

Overlay



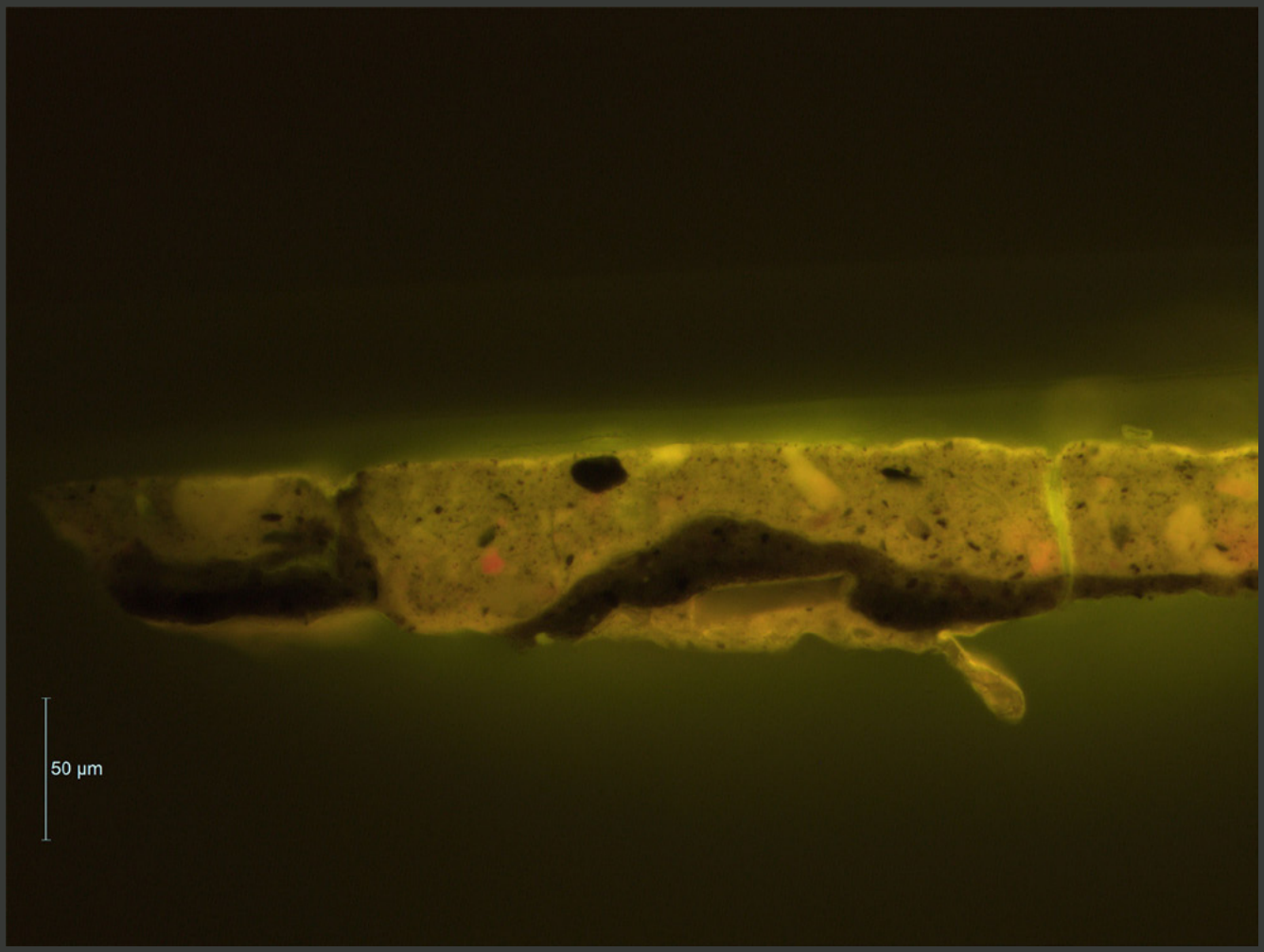

1
2
c
b
a
50 µm

Cross Section 15 (CS15)

Location: Dark folds in the red garment of the figure on the right

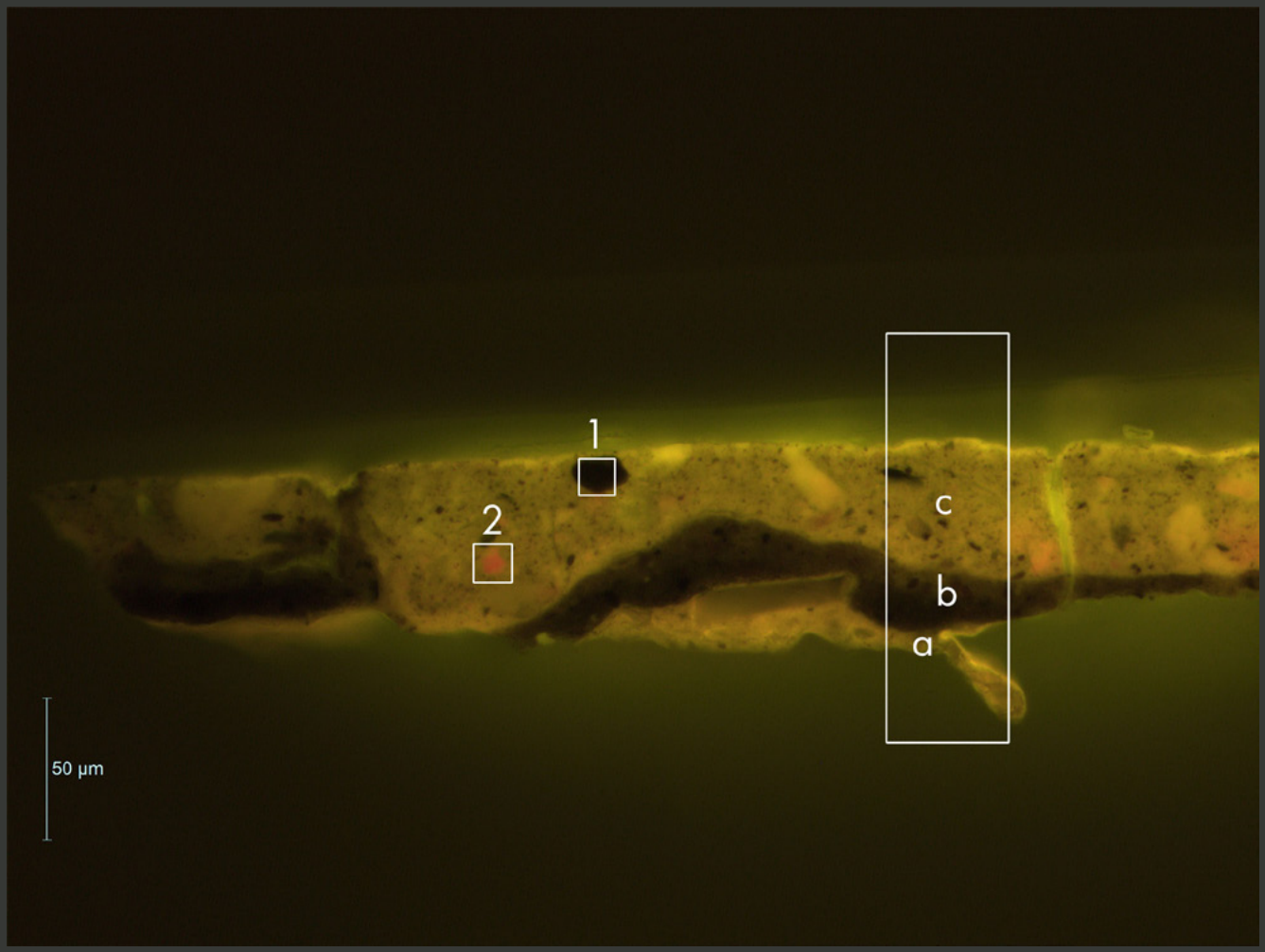
Excitation: blue (450–490 nm)
Emission: green (λ_{em} > 515 nm)

Overlay



GROUND LAYERS

Only a small portion of the upper ground was retained during sampling. According to the EDS maps, a large particle of potassium aluminum silicate, located in (a), is likely part of the upper ground structure.


1
2
c
b
a
50 µm

Cross Section 15 (CS15)

Location: Dark folds in the red garment of the figure on the right

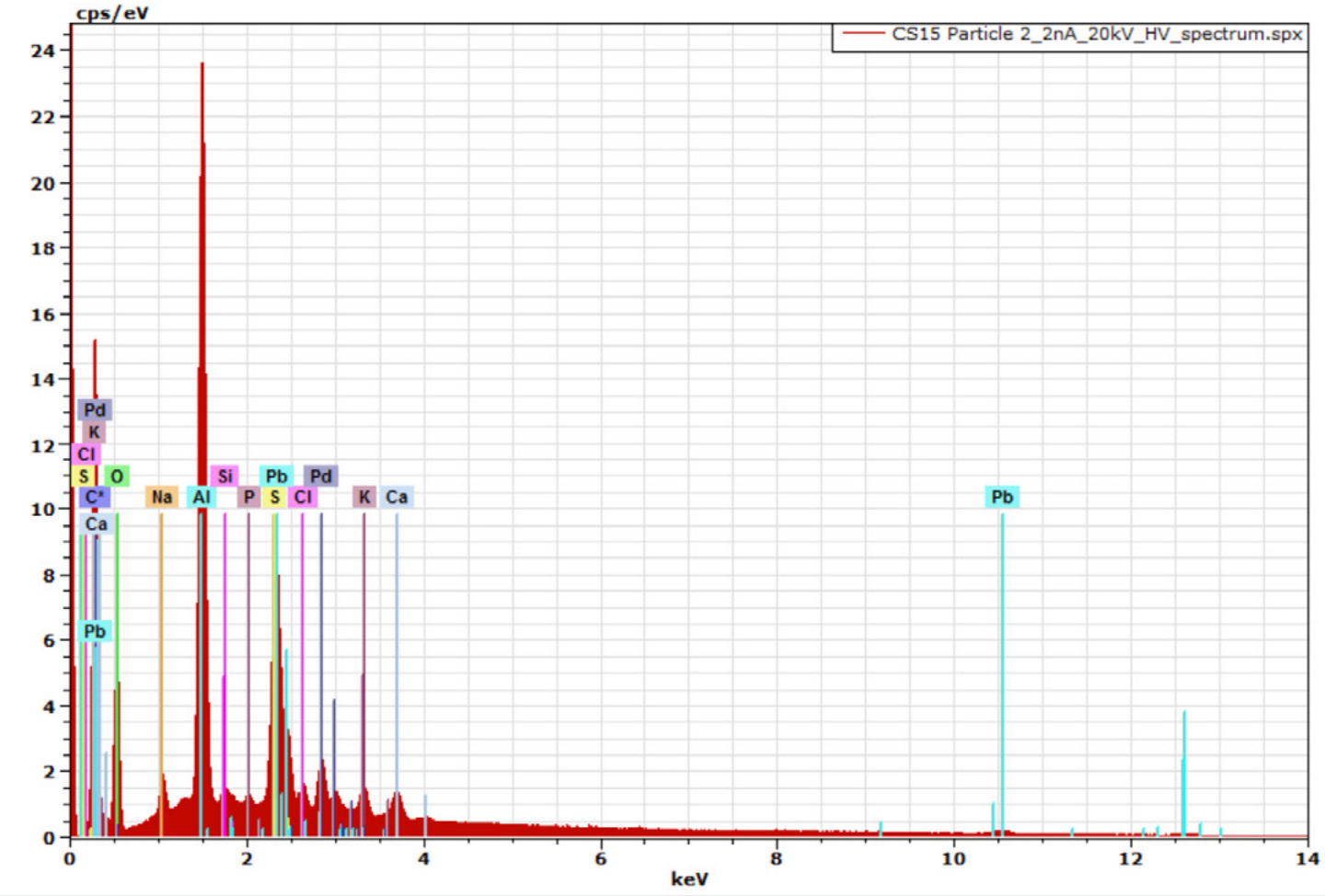
PAINT LAYERS

Applied in a single layer, the dark red-violet paint (c) is composed of a fairly even, yet sparse concentration of pigments. When viewed under UV, the binding medium in (c) of the cross section, which surrounds the pigment particles, emits an overall opaque, whitish-gray fluorescence. This confirms that the source of the fluorescence is primarily found in the binding medium. Minute particles of red scattered throughout (c) correspond to the element map of iron and are likely hematite (red ochre). Mercury and lead are completely absent from the paint layer, ruling out the presence of vermilion or lead white.

EDS scan analysis of the dark red-violet particle, located in the paint layer (c), number 2, produced a spectrum containing aluminum and trace amounts of potassium, sulfur, and calcium, indicative of a lake substrate (see EDS spectrum for particle 2).[8] A higher magnification SEM image of the same particle shows a rather ragged perimeter, also consistent with lake pigment particles (see secondary electron image of particle estimated to be red lake).[9] Interestingly, this red-violet particle emits an orange fluorescence when observed with blue excitation and green emission.[10]The large black particle (1) corresponds to the EDS map for calcium and phosphorus, indicating bone black. An EDS spectrum of this black particle further confirms its composition with prominent peaks of phosphorus and calcium.

Layer (b), which emits a dark violet color under UV radiation, shows a prominent element map of both manganese and iron, indicative of an umber pigment.

EDS SPECTRUM FOR PARTICLE 2

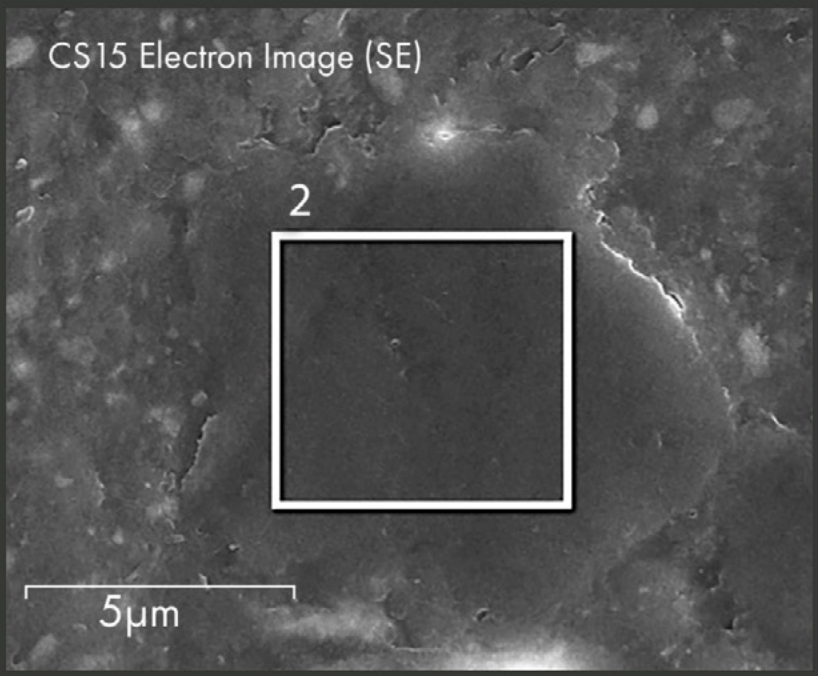


EDS spectrum for particle 2, estimated to be red lake. Note that the sample was coated with a 7 nm layer of palladium, which accounts for the palladium peaks.

Cross Section 15 (CS15)

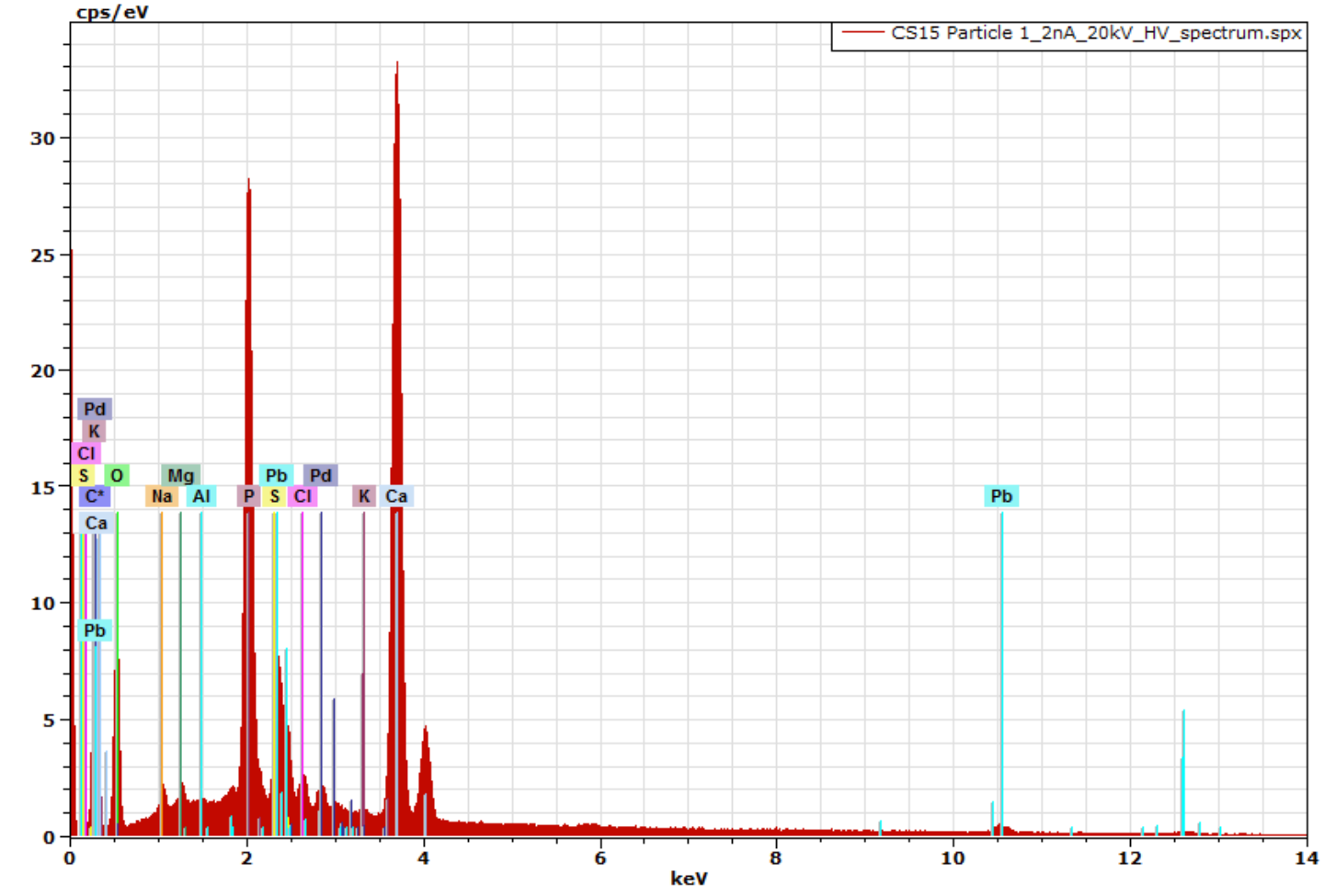
Location: Dark folds in the red garment of the figure on the right

SEM-SE IMAGE OF PARTICLE 2



Electron (SE) image of particle 2, estimated to be red lake. Note the ragged perimeter indicative of lake pigments.

EDS SPECTRUM FOR PARTICLE 1

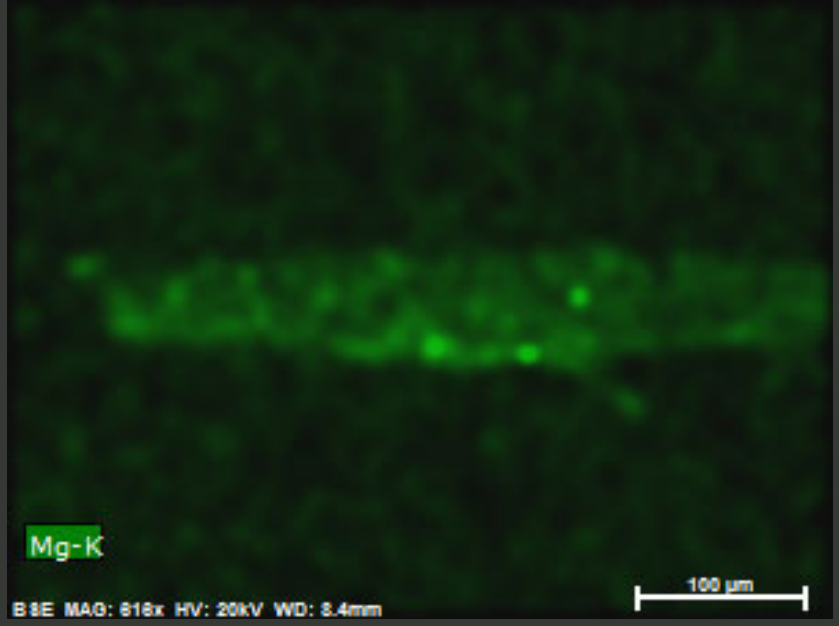


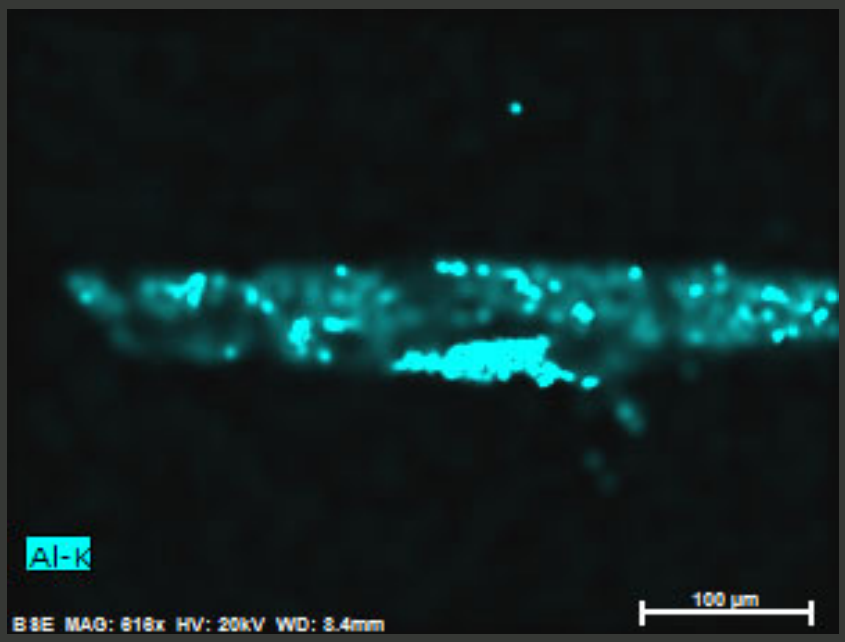
EDS spectrum for black particle. Note that the sample was coated with a 7 nm layer of palladium (Pd), which accounts for the palladium peaks.

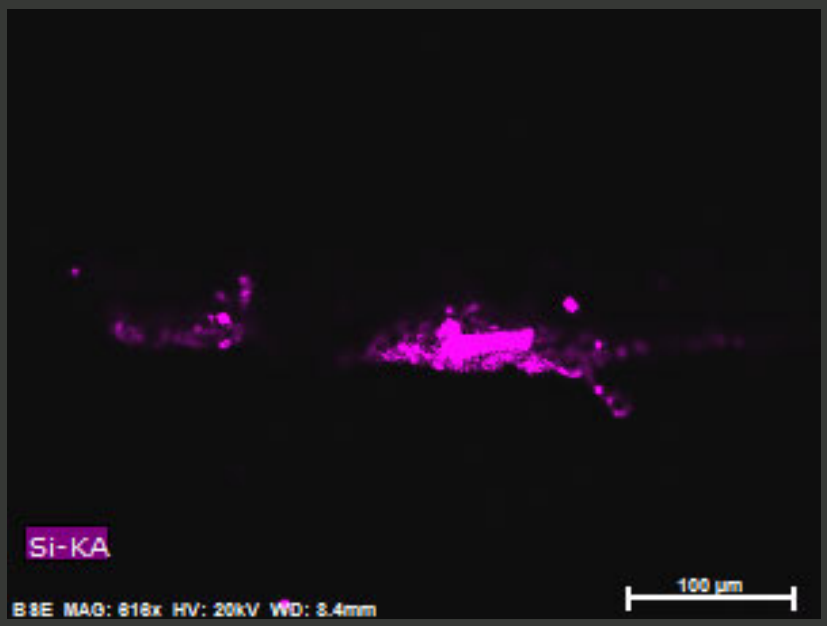
SEM-EDS MAPS

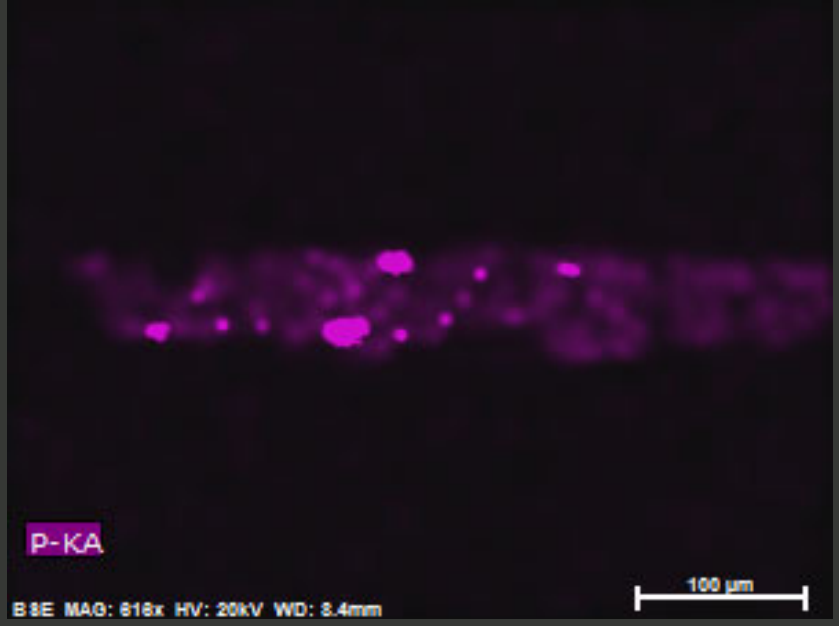
BSE
Na
Mg
Al
Si
P
S
K
Ca
Mn
Fe

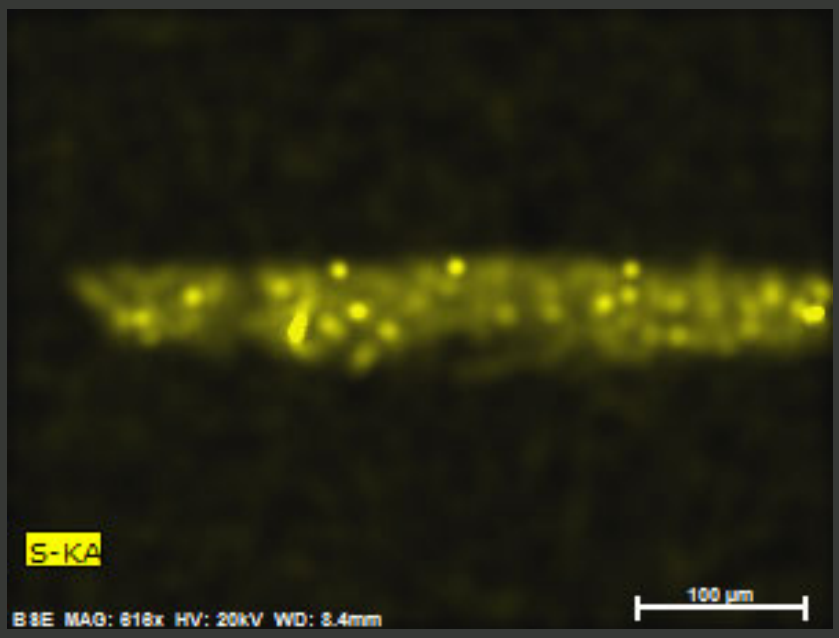
MAG: 282x
HV: 20 kV
WD: 8.7 mm
Scale bar: 200 µm


Mg-K
BSE MAG: 816x HV: 20kV WD: 8.4mm
100 µm

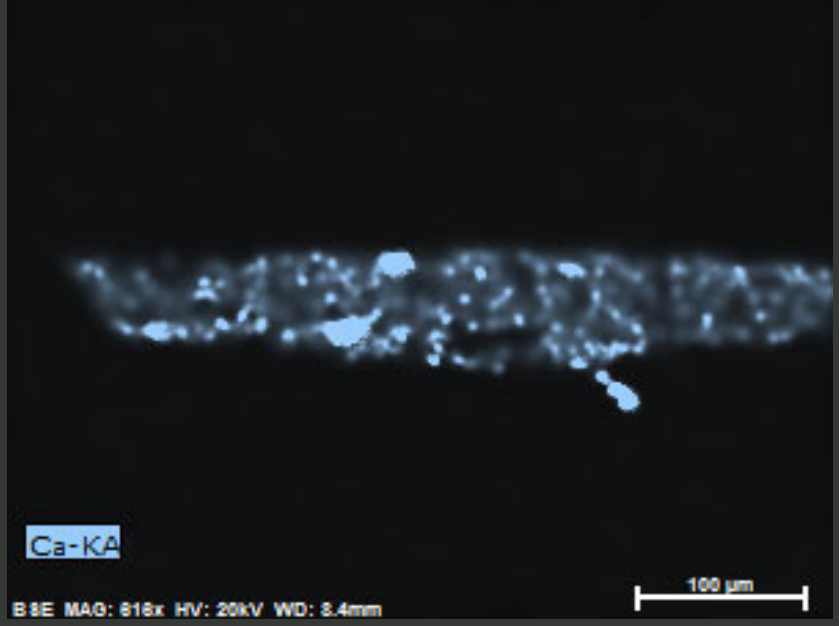

Al-K
BSE MAG: 816x HV: 20kV WD: 8.4mm
100 µm

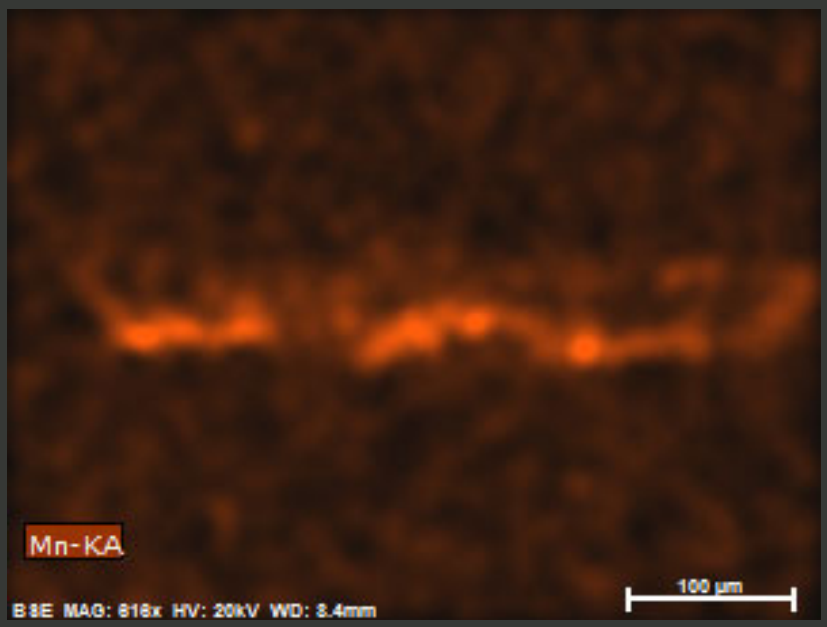

Si-KA
BSE MAG: 816x HV: 20kV WD: 8.4mm
100 µm

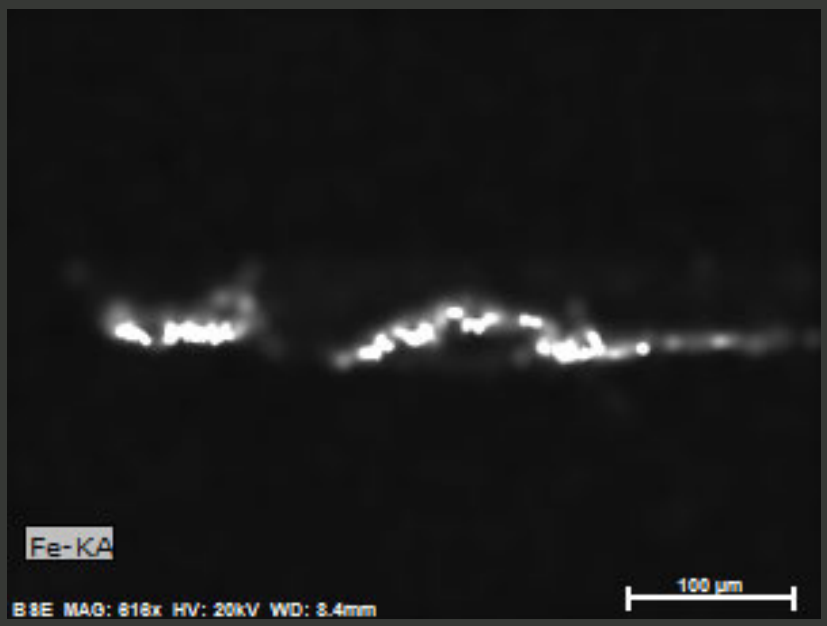

P-KA
100 µm
B 8E MAG: 816x HV: 20kV WD: 8.4mm


S-KA
100 µm
B 8E MAG: 816x HV: 20kV WD: 8.4mm

K-KA
100 µm
B 8E MAG: 816x HV: 20kV WD: 8.4mm


Ca-KA
100 µm
BSE MAG: 816x HV: 20kV WD: 8.4mm

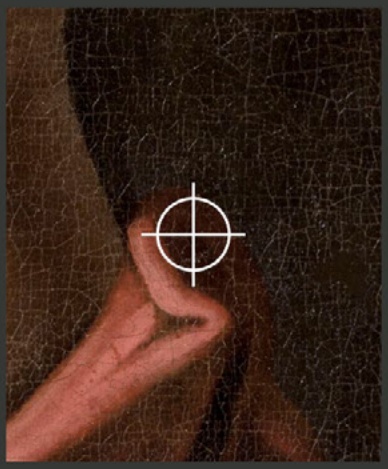

Mn-KA
100 µm
BSE MAG: 816x HV: 20kV WD: 8.4mm

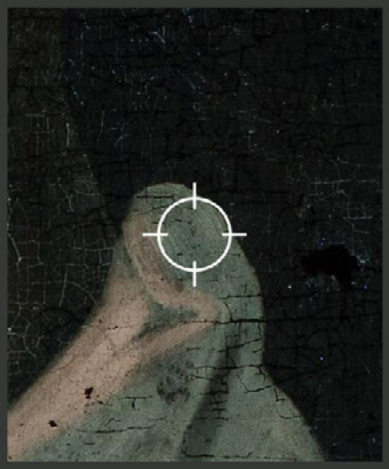

Fe-KA
100 µm
BSE MAG: 816x HV: 20kV WD: 8.4mm

Cross Section 16 (CS16)

Location: Shadow in the top loop of Saint Andrew's garment

Sample 16, from the top loop of Saint Andrew's drapery in shadow, was taken after treatment mainly to determine the source of the bright, milky green fluorescence seen in the UV photograph after treatment.



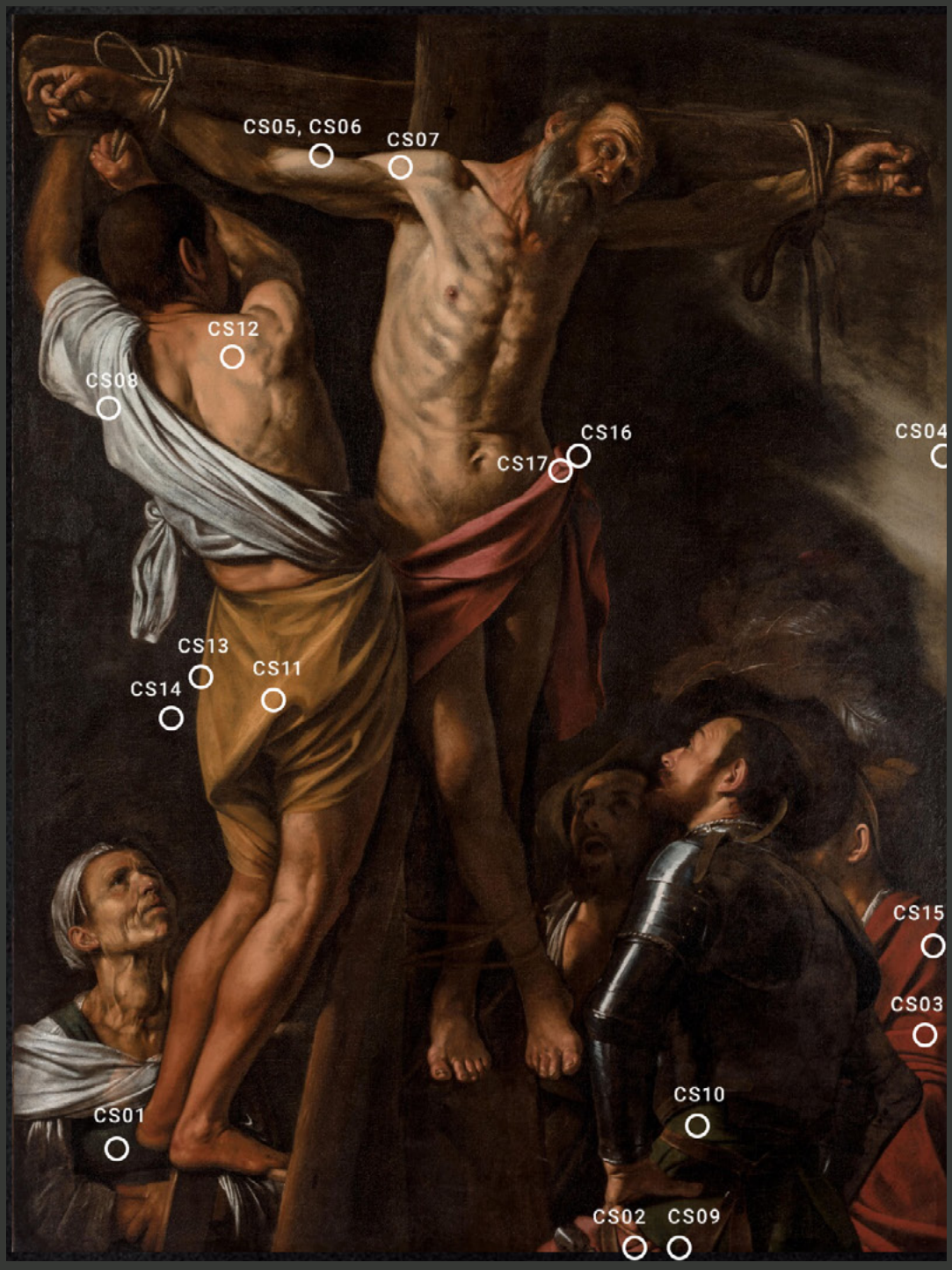


CROSS SECTIONS

GROUND LAYERS

PAINT LAYERS

SEM-EDS MAPS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

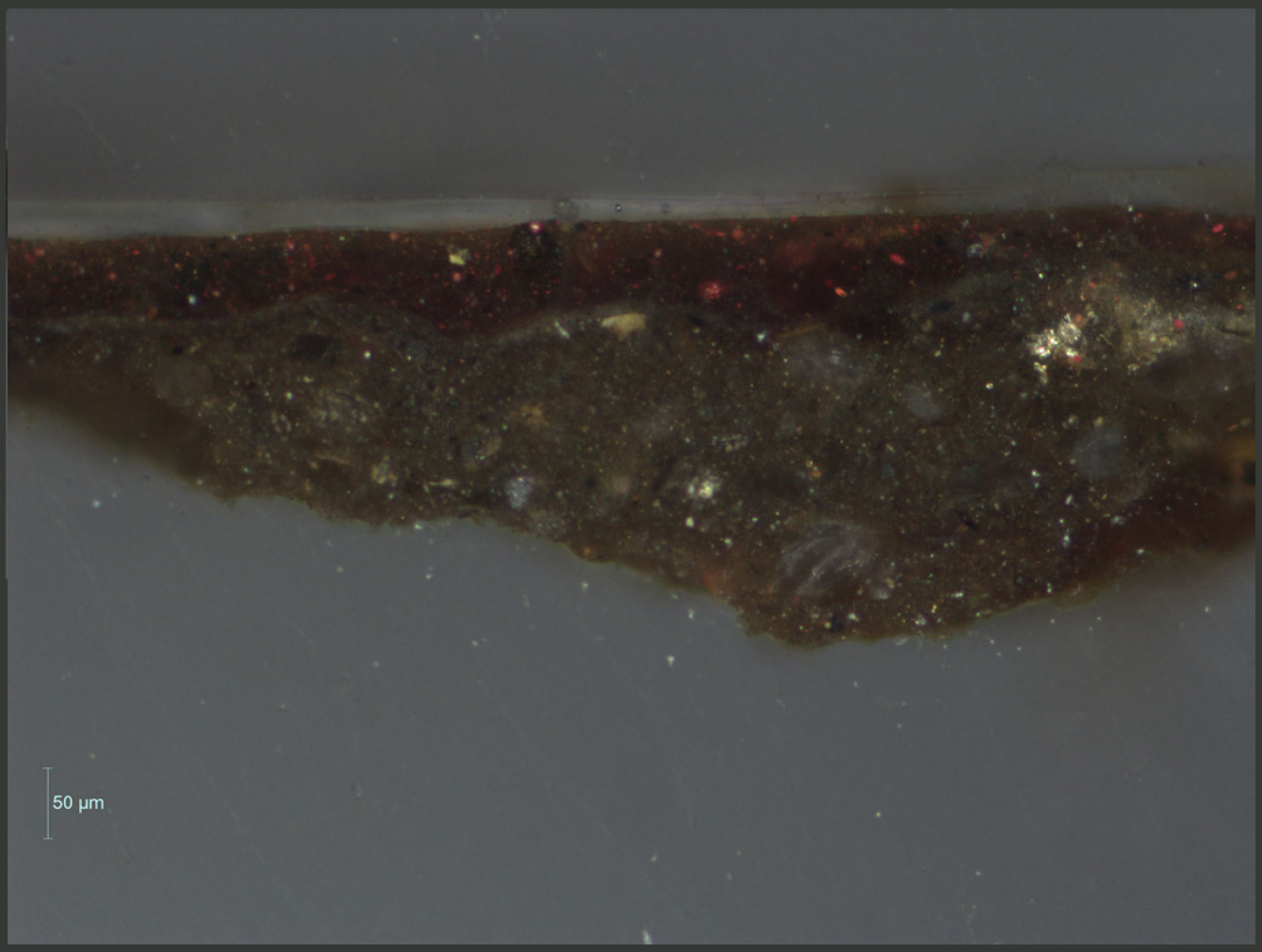
Cross Section 16 (CS16)

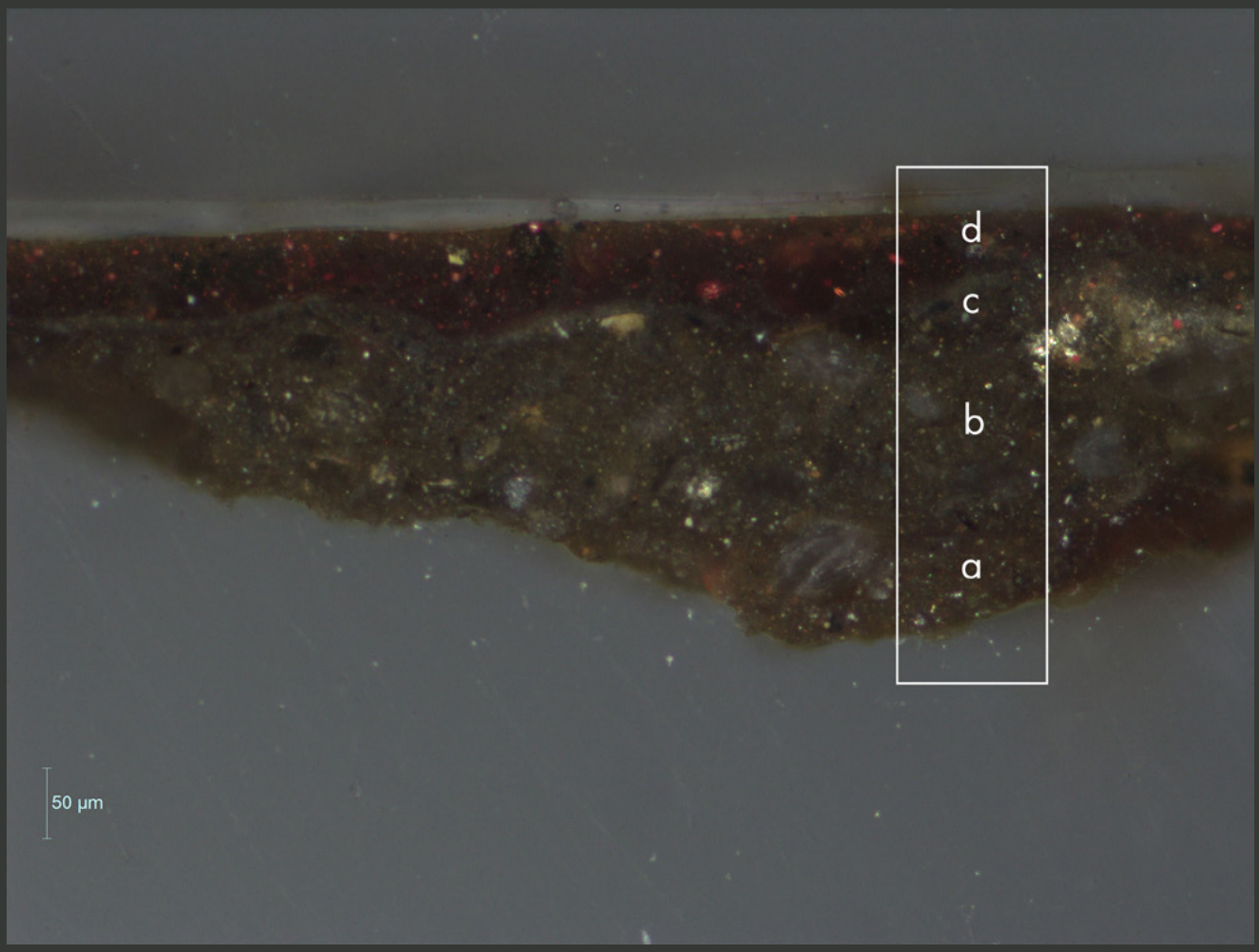
Location: Shadow in the top loop of Saint Andrew's garment

Sample 16, from the top loop of Saint Andrew's drapery in shadow, was taken after treatment mainly to determine the source of the bright, milky green fluorescence seen in the UV photograph after treatment.

CROSS SECTIONS

Normal Light Overlay



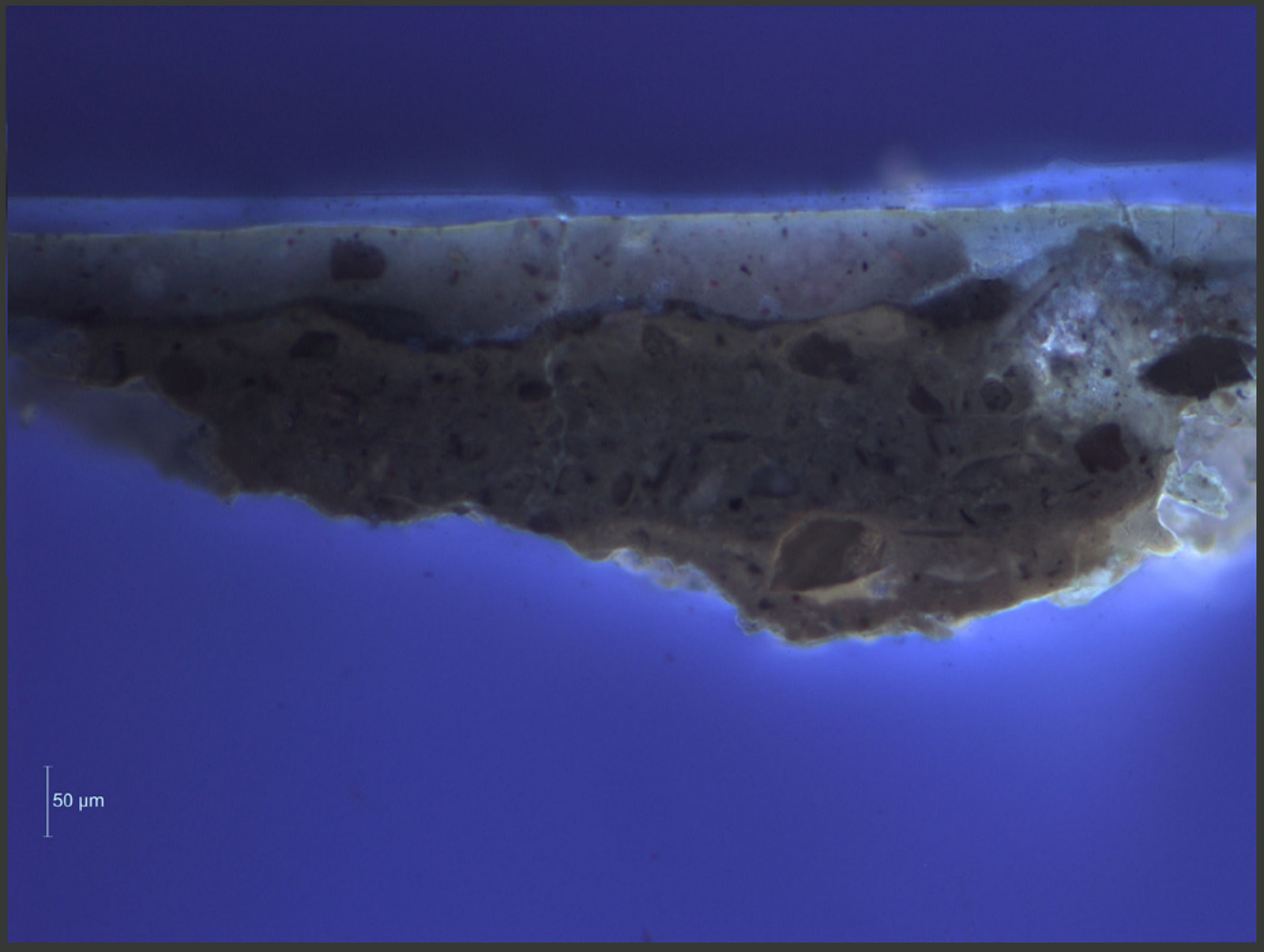

d
c
b
a
50 µm

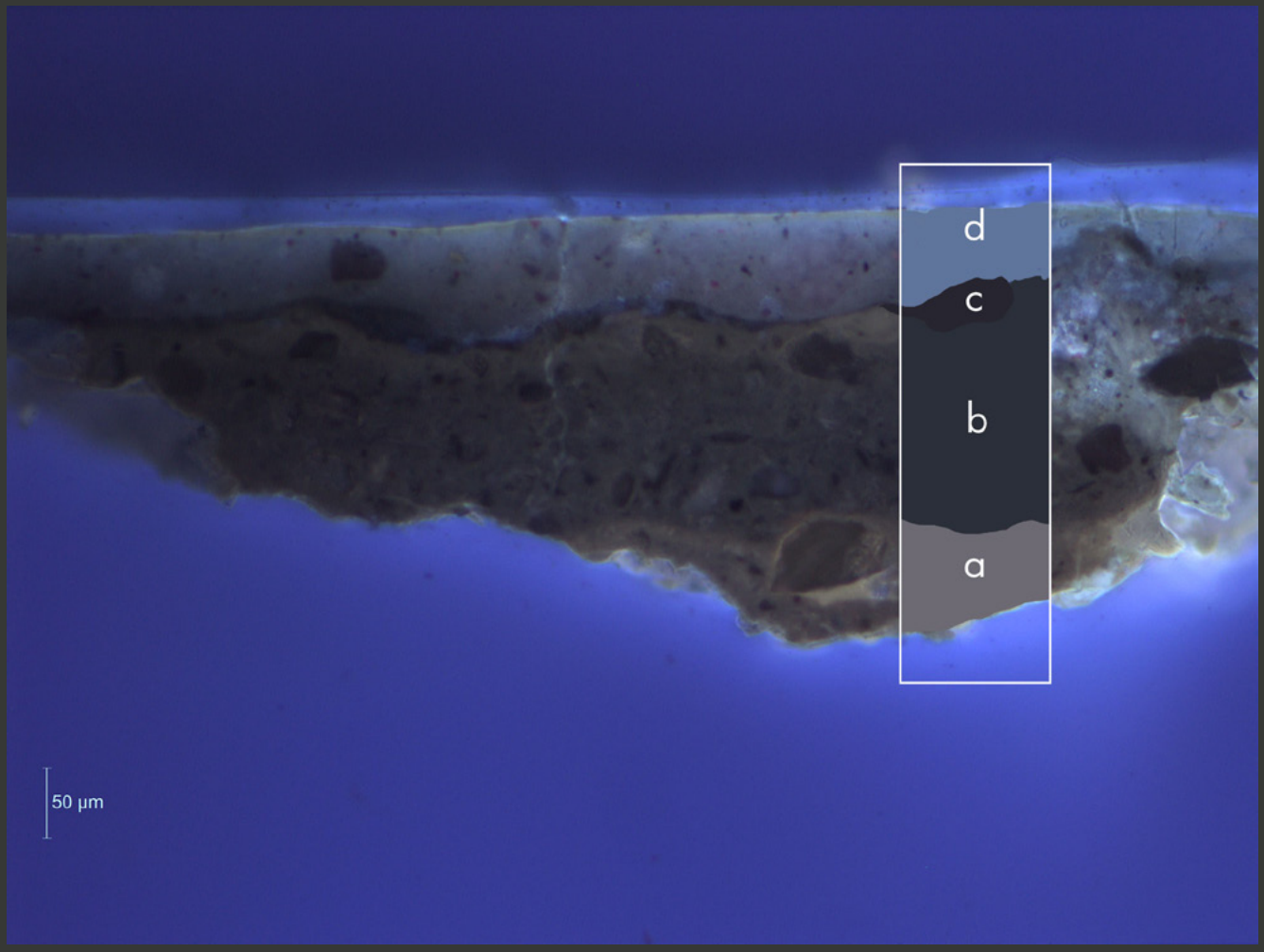
Cross Section 16 (CS16)

Location: Shadow in the top loop of Saint Andrew's garment

Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm)

Overlay



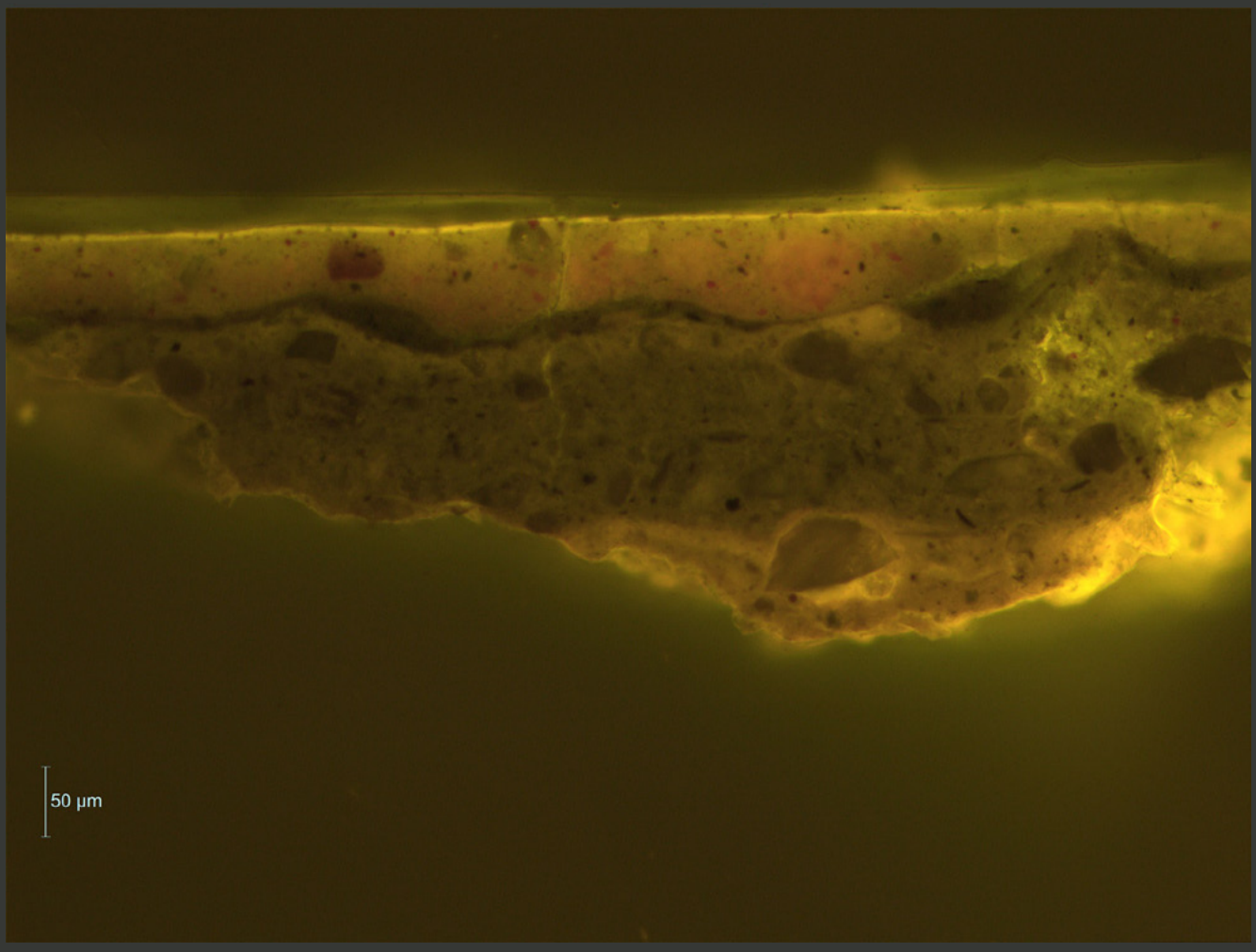

d
c
b
a
50 µm

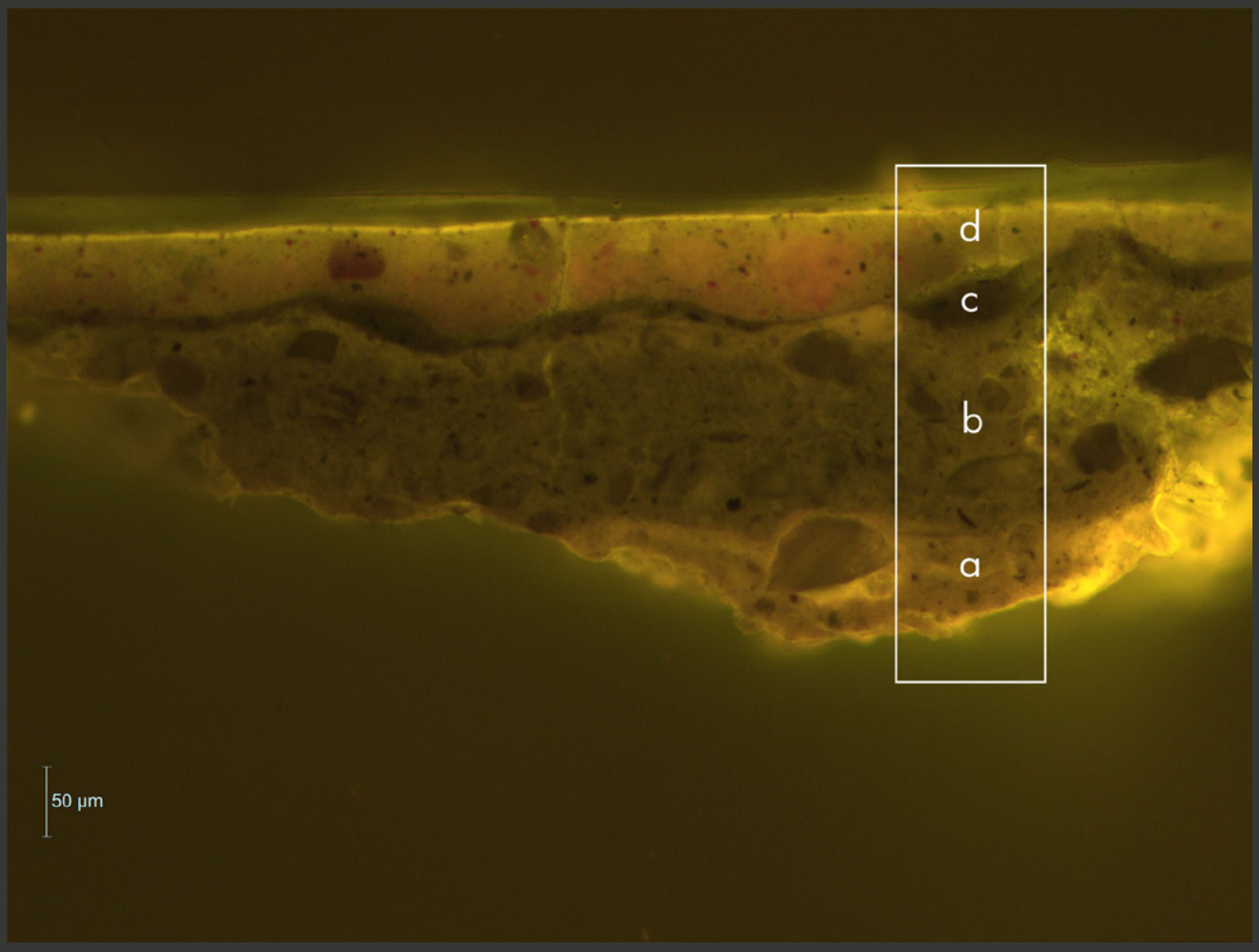
Cross Section 16 (CS16)

Location: Shadow in the top loop of Saint Andrew's garment

Excitation: blue (450–490 nm)
Emission: green (λ_{em} > 515 nm)

Overlay




d
c
b
a
50 µm

Cross Section 16 (CS16)

Location: Shadow in the top loop of Saint Andrew's garment

GROUND LAYERS

As expected, the ground layers (a and b) are mainly composed of aluminosilicates, chalk, and earth pigments. EDS mapping shows an equal distribution of sodium, magnesium, aluminum, silicon, calcium, and potassium. A large particle containing only silicon (possibly quartz) is located in the lower ground (a).

PAINT LAYERS

Under normal light the paint layer (d) is medium-rich, dark reddish brown with an even distribution of finely ground bright red and larger deep reddish-violet particles. A few of the bright red particles in the paint layer directly correspond to the EDS maps for mercury, indicating a sparse distribution of vermilion. EDS mapping shows an even, homogenous distribution of aluminum, sulfur, and potassium in the paint layer, indicative of a lake pigment. Overlapping maps of aluminum and sulfur correspond to some of the darker reddish-violet particles.

The thin, light gray layer (c) appears as dark violet under UV irradiation, absorbing much of the UV. This thin layer is almost entirely composed of lead and phosphorus. A moderate amount of lead is also present in the lower portion of the paint layer (d), possibly drawn into the paint layer from the underlying gray layer, which appears to contain a higher concentration of lead.

When viewed under UV, the paint binder clearly fluoresces an opaque milky white. Some of the smaller bright red particles (seen under normal light) absorb the UV and emit a dark violet color; other particles emit more of a faint orange-red.

Cross Section 16 (CS16)

Location: Shadow in the top loop of Saint Andrew's garment

Interestingly, when viewed with the blue excitation / green emission, the larger dark violet particles produce a prominent orange fluorescence. At the very top edge of the paint layer (d), a thin, bright line of intense fluorescence, only 3 microns thick, is visible under both UV radiation and blue excitation. This bright fluorescence appears to be more prominent than an "edge effect" caused by the intense mercury vapor light source, but rather like a discolored crust, especially when viewed with UV excitation / blue emission. Pigment particles that extend into and terminate at this layer further suggest it is part of the paint layer.

SEM-EDS MAPS

BSE

Na

Mg

Al

Si

P

S

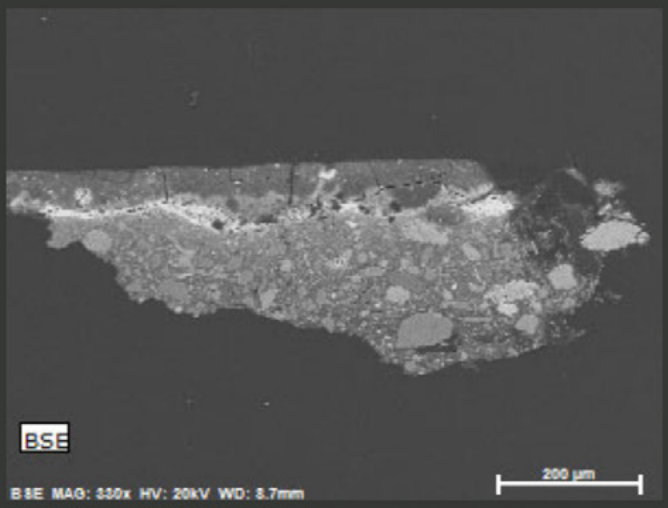
K

Ca

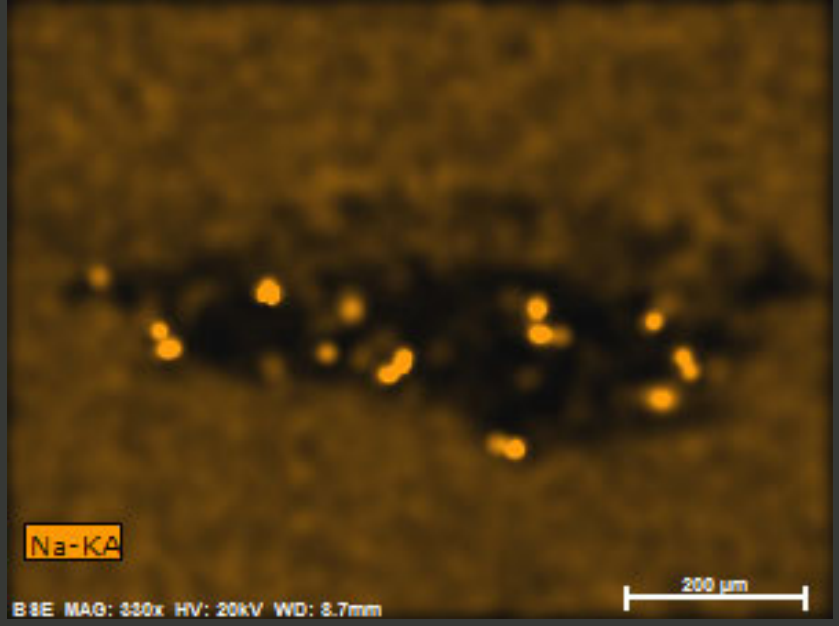
Fe

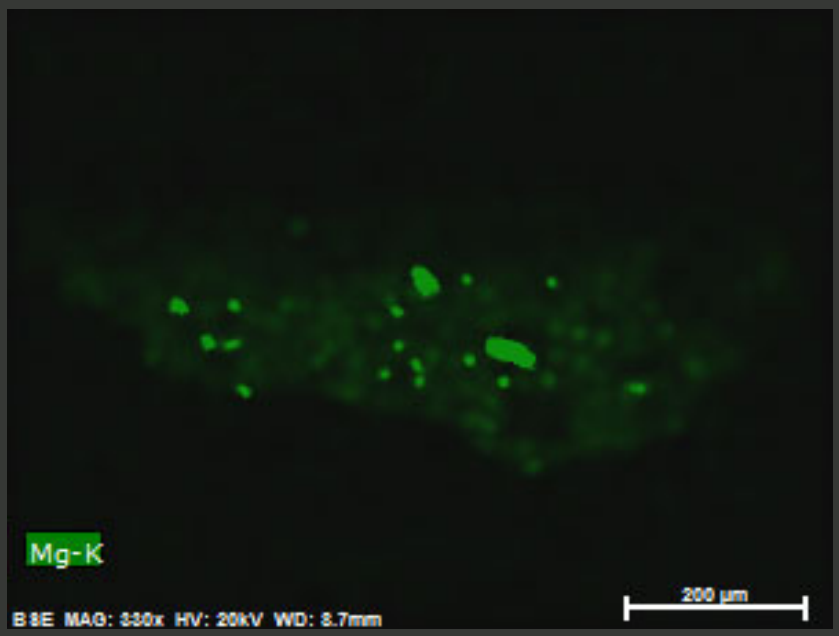
Hg

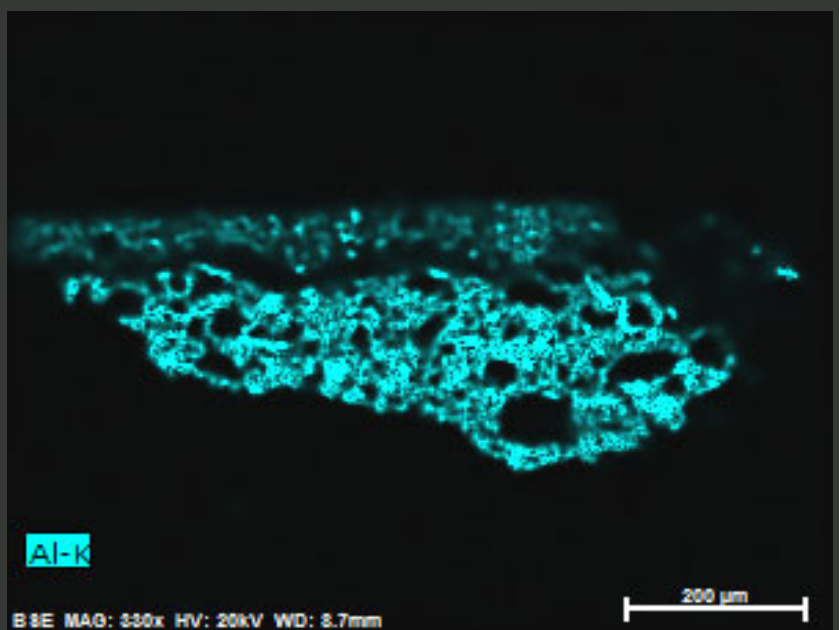
Pb

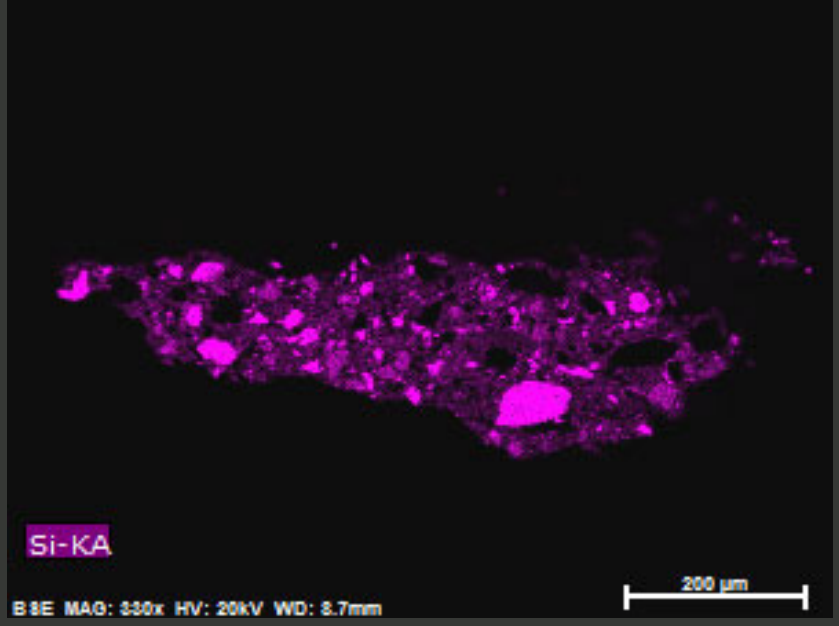


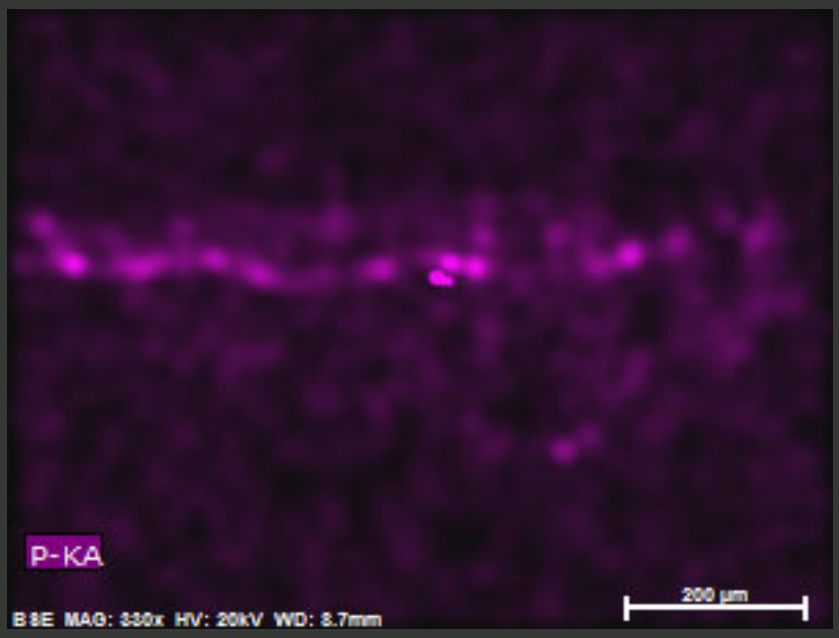
MAG: 330x
HV: 20 kV
WD: 8.7 mm
Scale bar: 200 µm

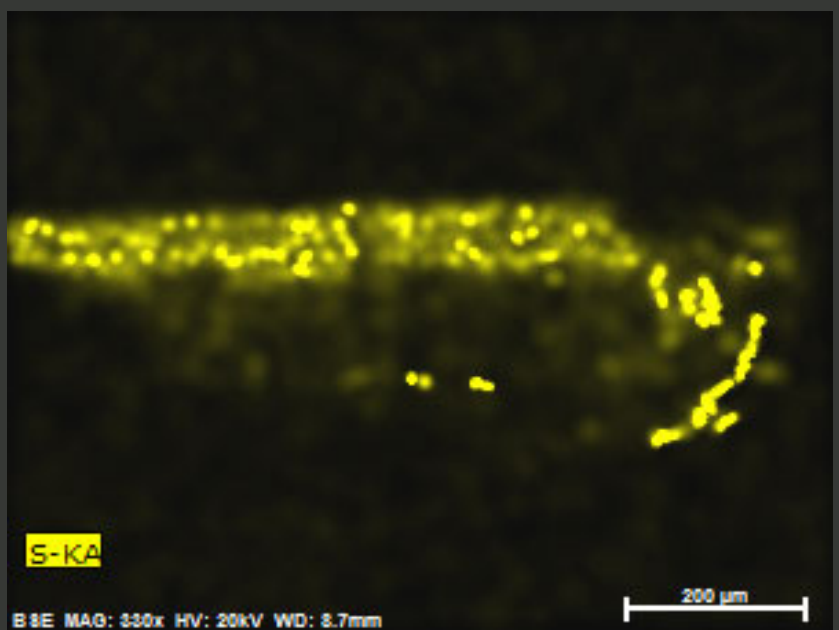

Na-KA
200 µm
B 8E MAG: 330x HV: 20kV WD: 8.7mm

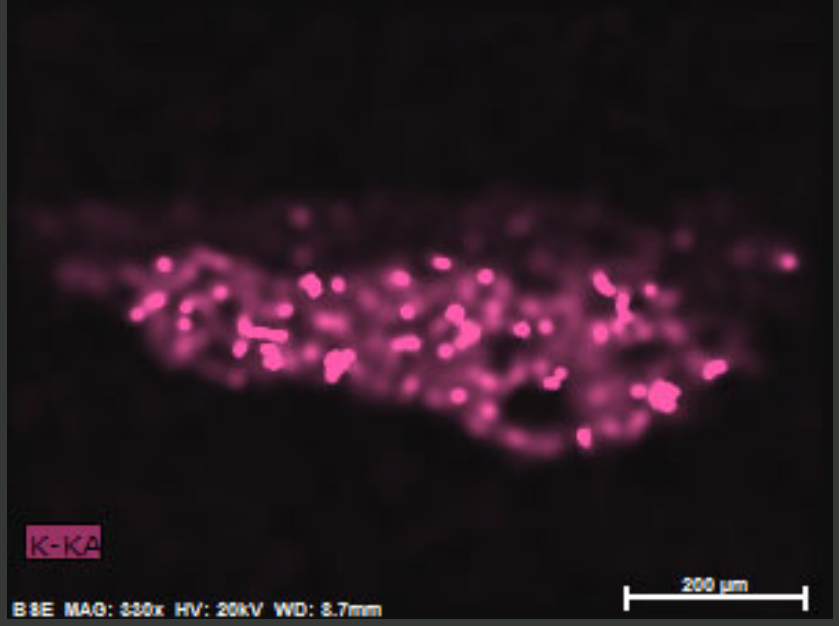

Mg-K
200 µm
B 8E MAG: 330x HV: 20kV WD: 8.7mm

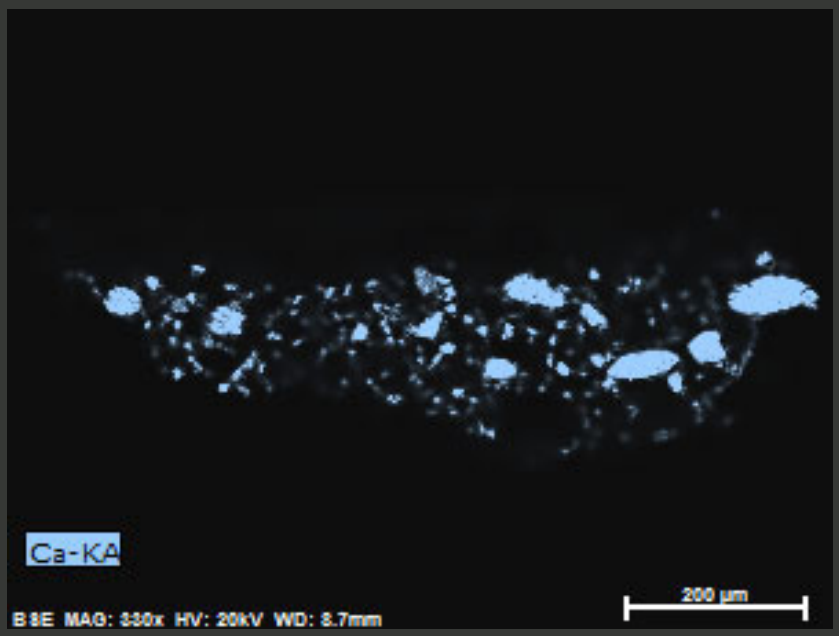

Al-K
200 µm
B 8E MAG: 330x HV: 20kV WD: 8.7mm

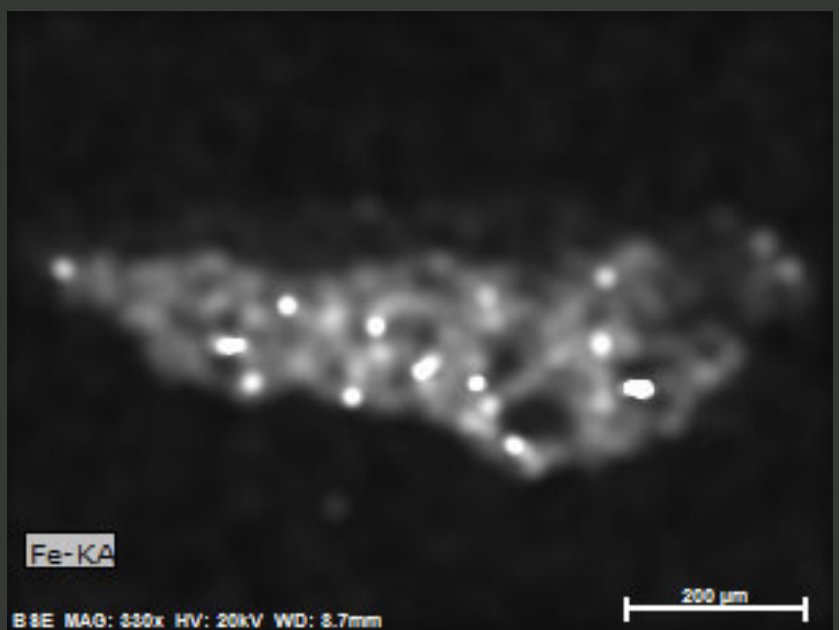

Si-KA
B 8E MAG: 330x HV: 20kV WD: 8.7mm
200 µm

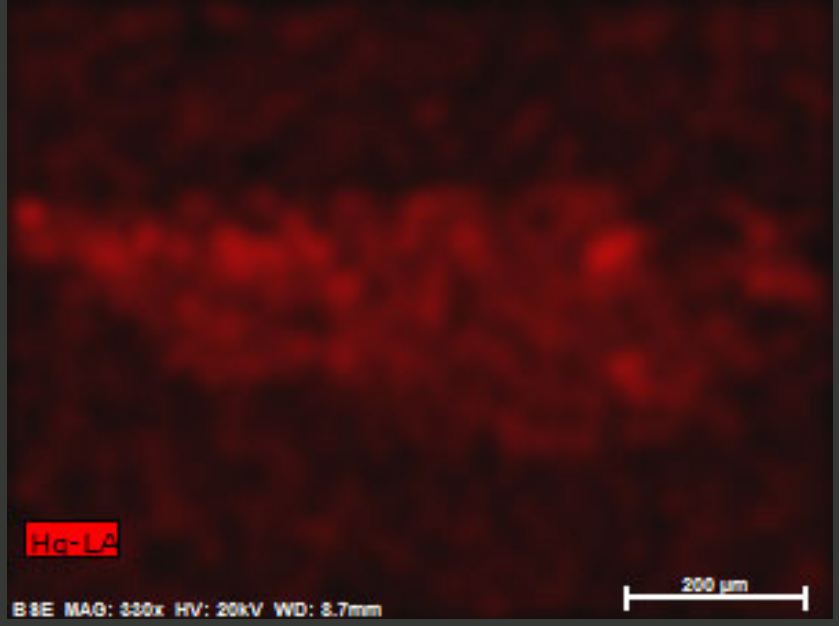

P-KA
B 8E MAG: 330x HV: 20kV WD: 8.7mm
200 µm

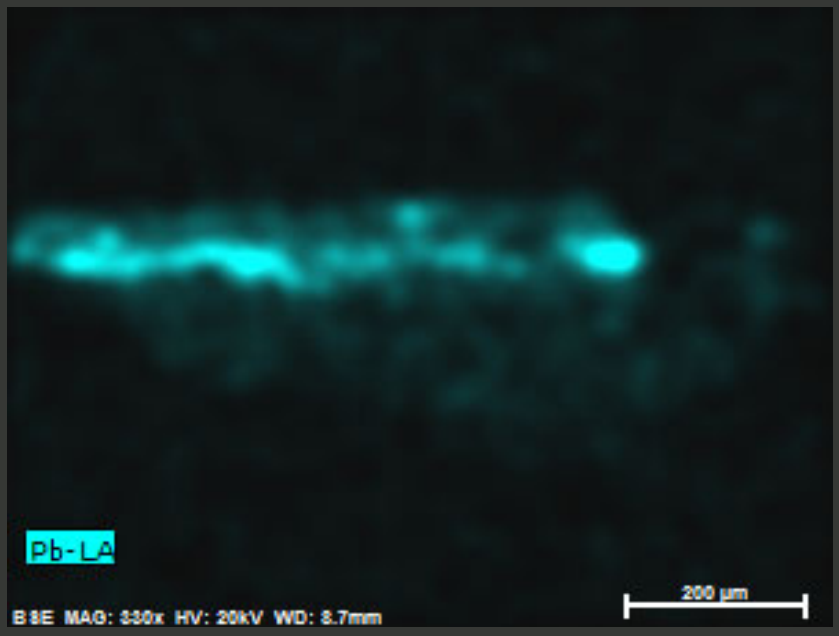

S-KA
B 8E MAG: 330x HV: 20kV WD: 8.7mm
200 µm


K-KA
B 8E MAG: 330x HV: 20kV WD: 8.7mm
200 µm


Ca-KA
B 8E MAG: 330x HV: 20kV WD: 8.7mm
200 µm


Fe-KA
B 8E MAG: 330x HV: 20kV WD: 8.7mm
200 µm

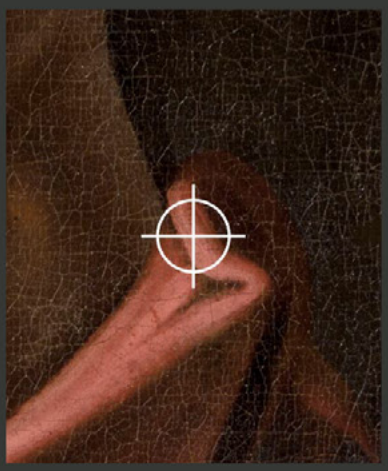

Hg-LA
200 µm
B 8E MAG: 330x HV: 20kV WD: 8.7mm


Pb-LA
200 µm
B 8E MAG: 330x HV: 20kV WD: 8.7mm

Cross Section 17 (CS17)

Location: Highlight from Saint Andrew's garment, after treatment

Sample 17 was taken after treatment to confirm the composition of the paint layer and to locate the source of the opaque fluorescence emanating from Saint Andrew's drapery when illuminated with UV radiation. Only the upper portion of the ground layer was retained while retrieving the sample.

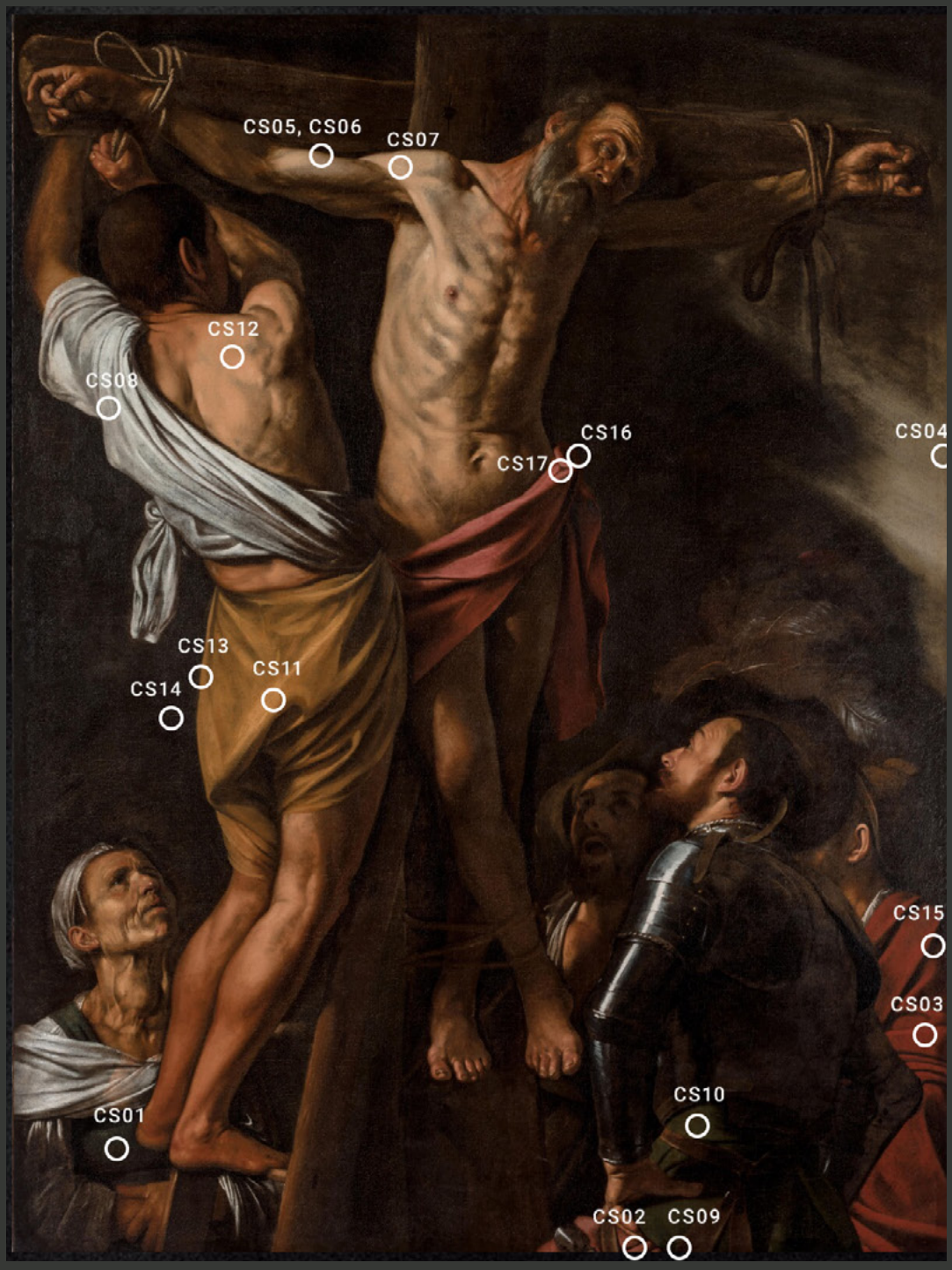


CROSS SECTIONS

GROUND LAYERS

PAINT LAYERS

SEM-EDS MAPS


CS05, CS06
CS07
CS12
CS08
CS16
CS17
CS04
CS13
CS11
CS14
CS15
CS03
CS10
CS01
CS02
CS09

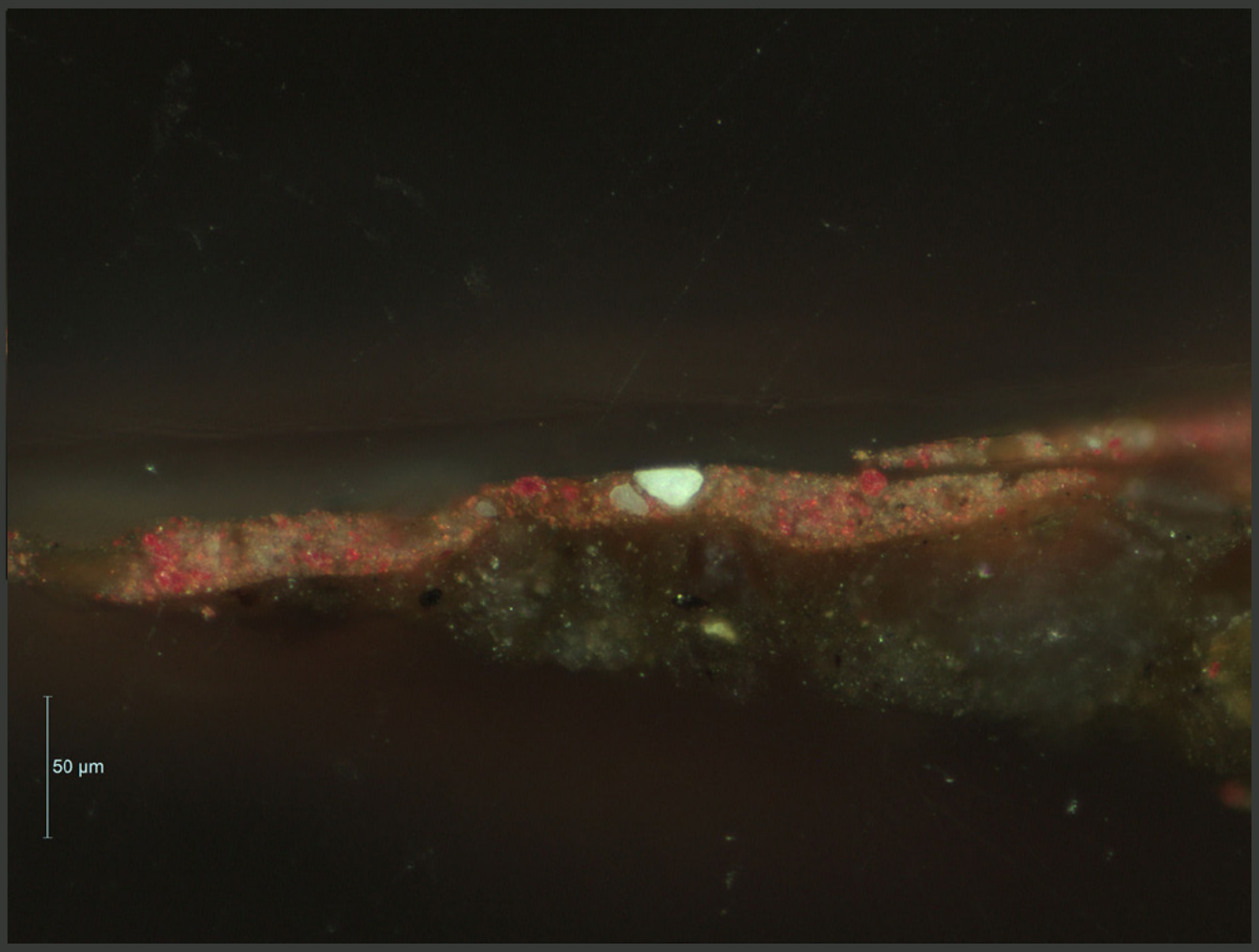
Cross Section 17 (CS17)

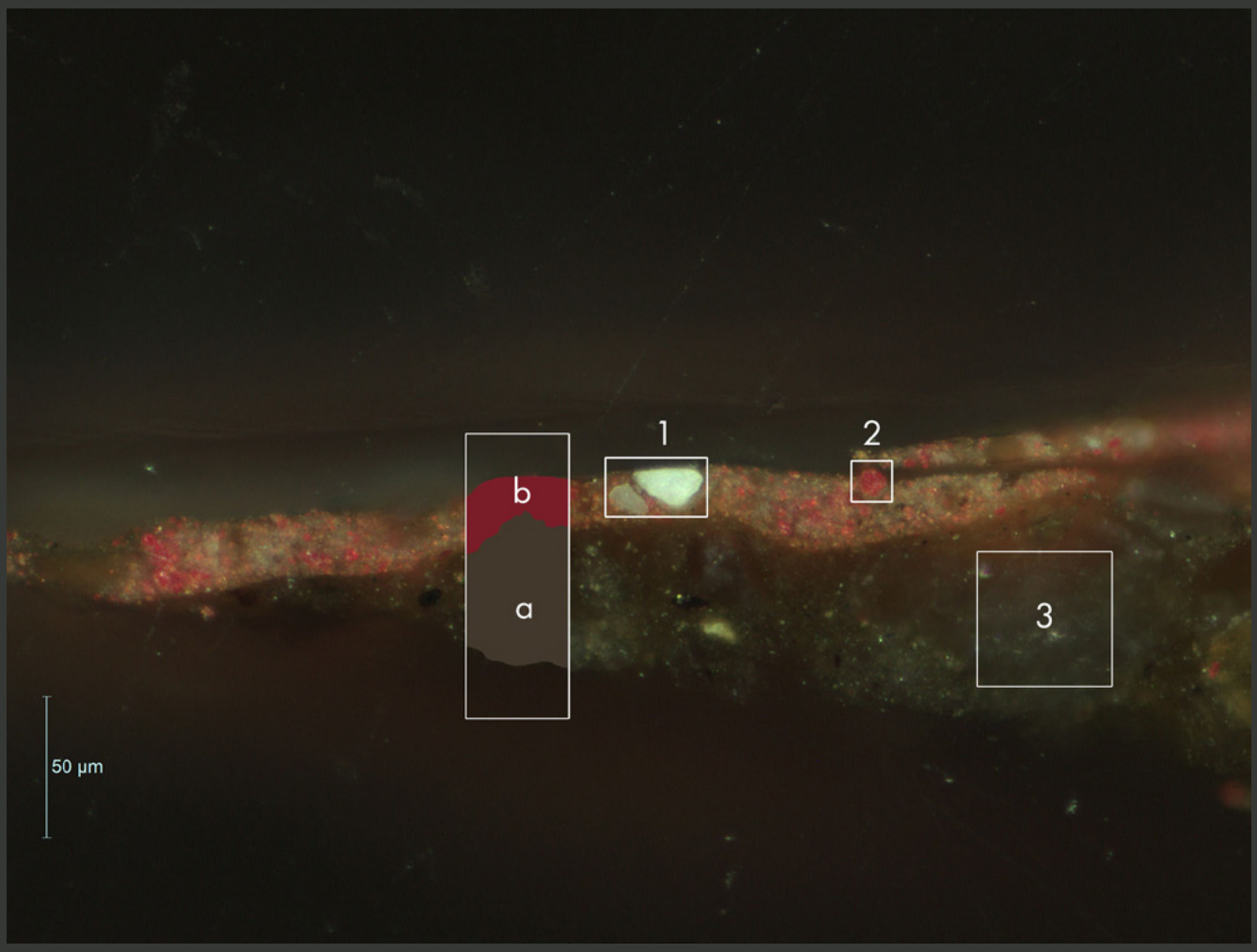
Location: Highlight from Saint Andrew's garment, after treatment

Sample 17 was taken after treatment to confirm the composition of the paint layer and to locate the source of the opaque fluorescence emanating from Saint Andrew's drapery when illuminated with UV radiation. Only the upper portion of the ground layer was retained while retrieving the sample.

CROSS SECTIONS

Normal Light Overlay



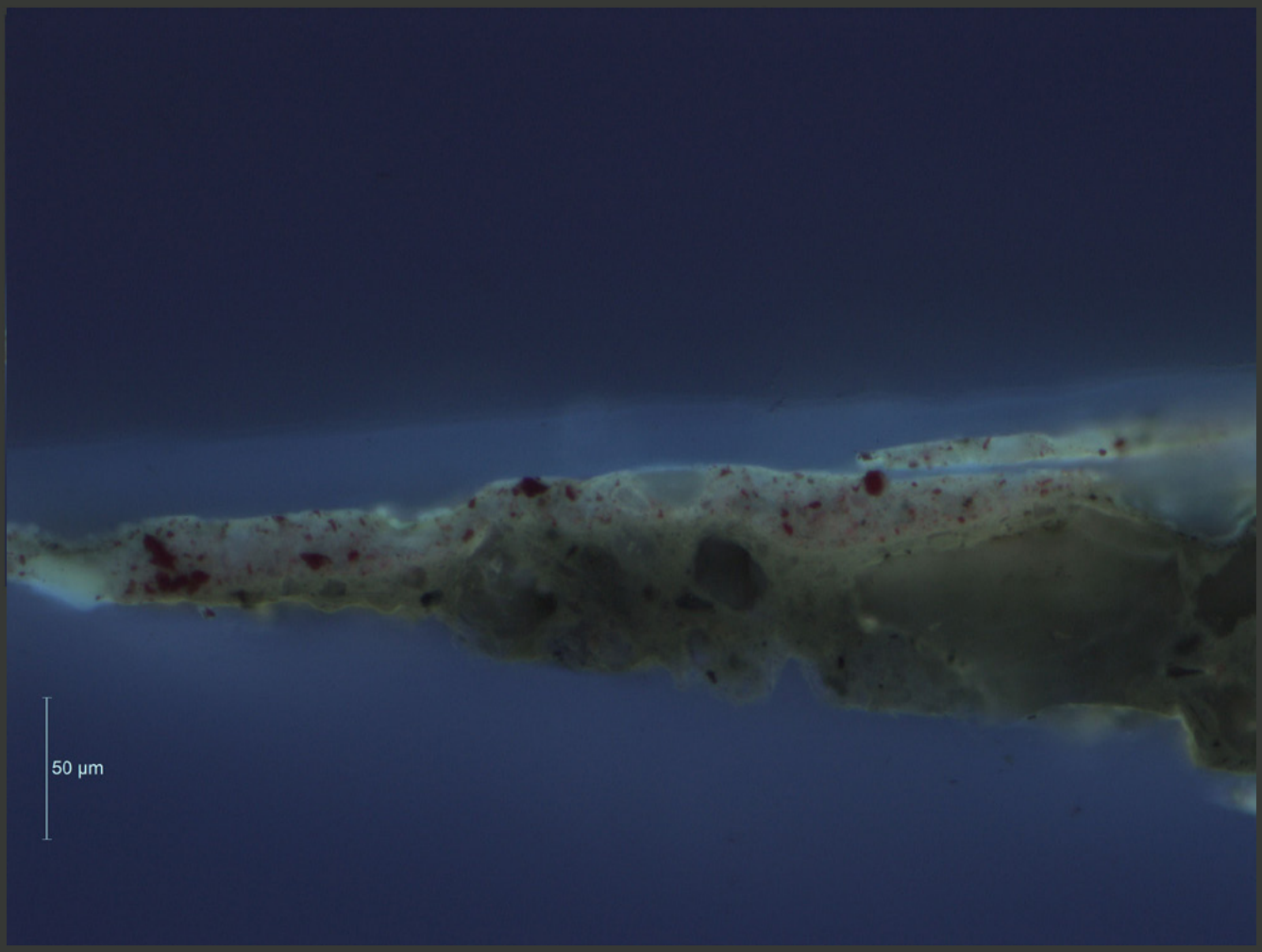

1
2
b
a
3
50 µm

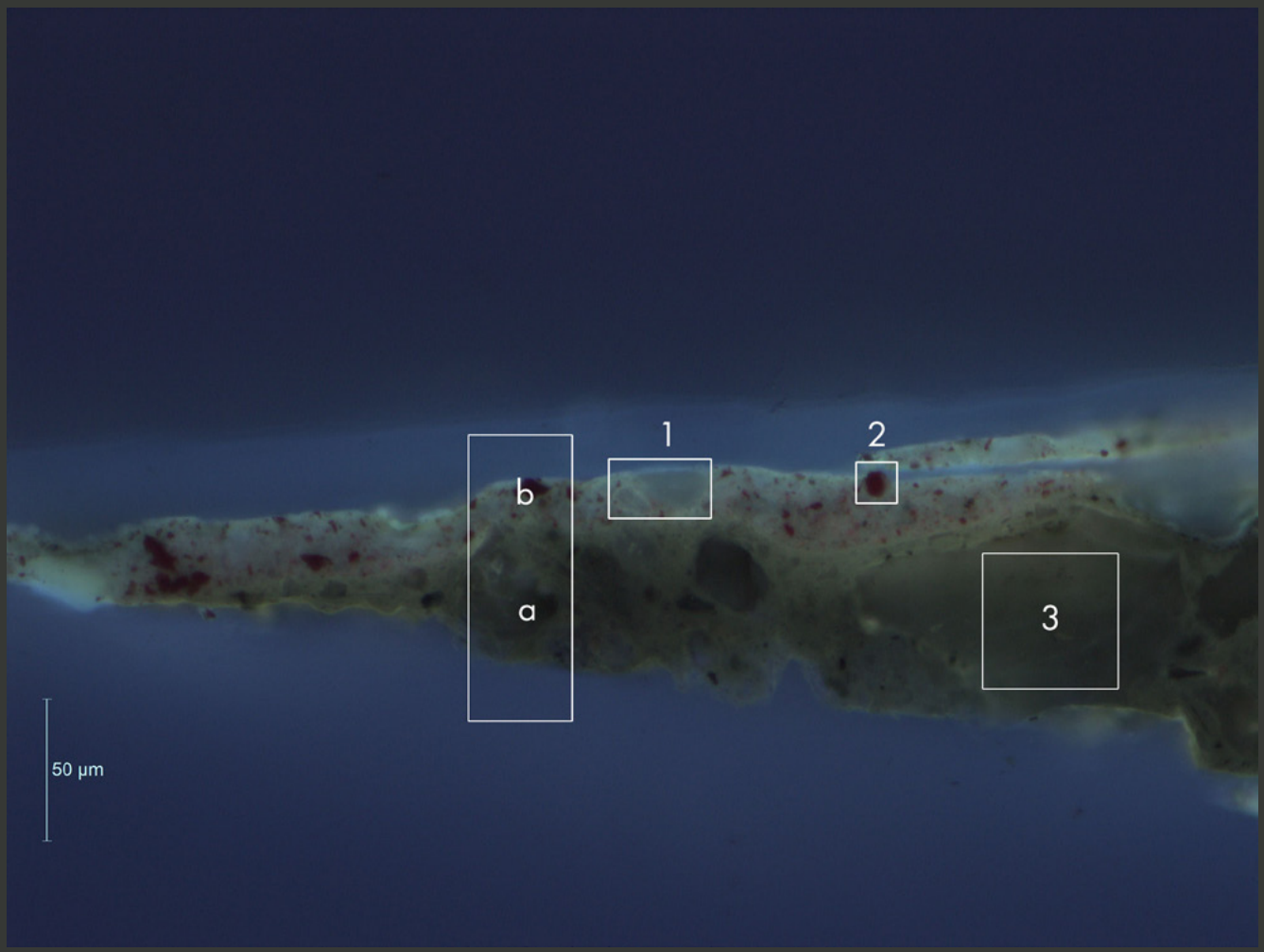
Cross Section 17 (CS17)

Location: Highlight from Saint Andrew's garment, after treatment

Excitation: UV (365 nm)
Emission: blue (λ_{em} > 420 nm)

Overlay



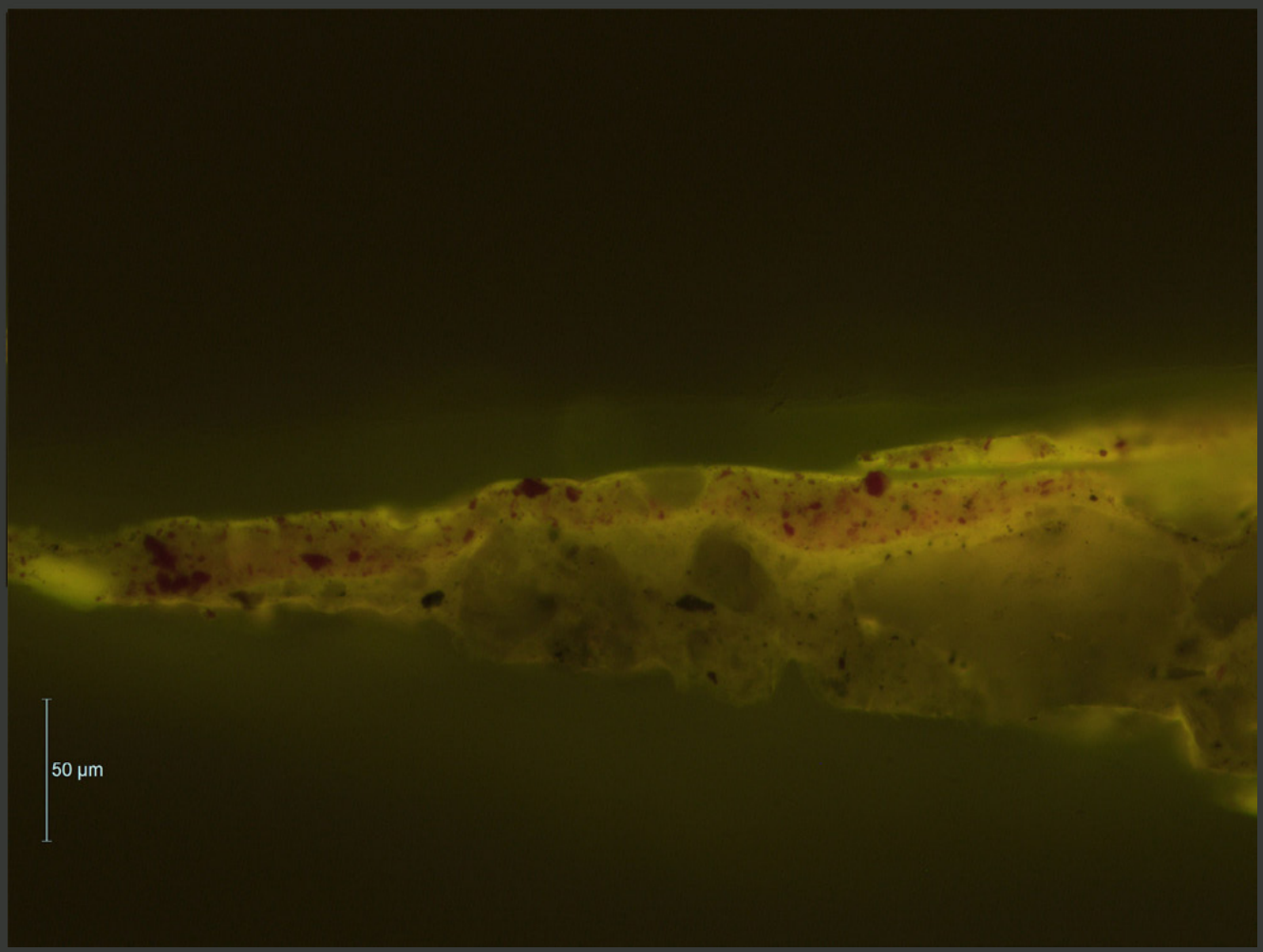

b
a
1
2
3
50 µm

Cross Section 17 (CS17)

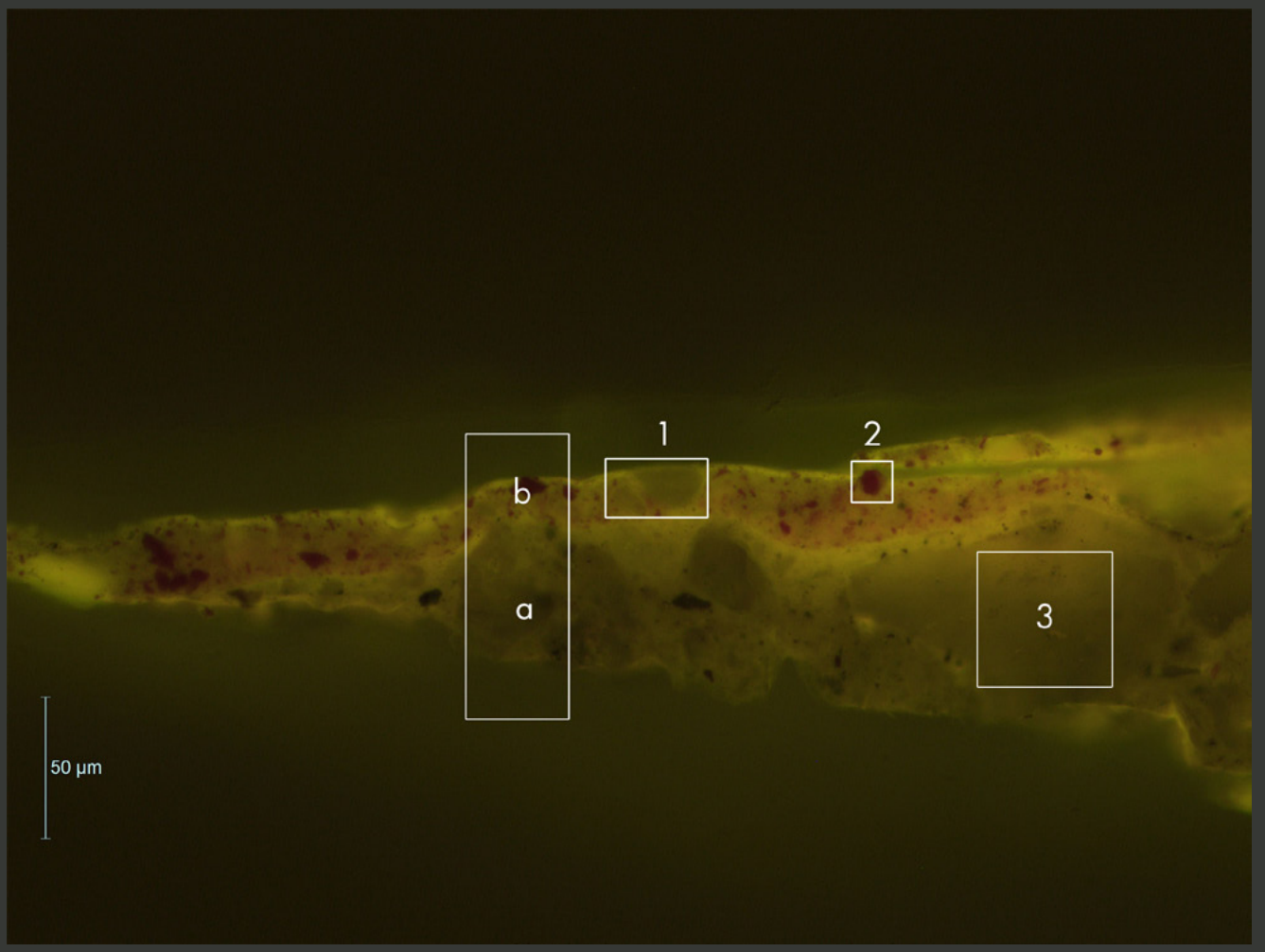
Location: Highlight from Saint Andrew's garment, after treatment

Excitation: blue (450–490 nm)
Emission: green (λ_{em} > 515 nm)

Overlay



As with samples 15 and 16, the binding medium is the source of the fluorescence seen in the after-treatment UV photographs.


b
a
1
2
3
50 µm

Cross Section 17 (CS17)

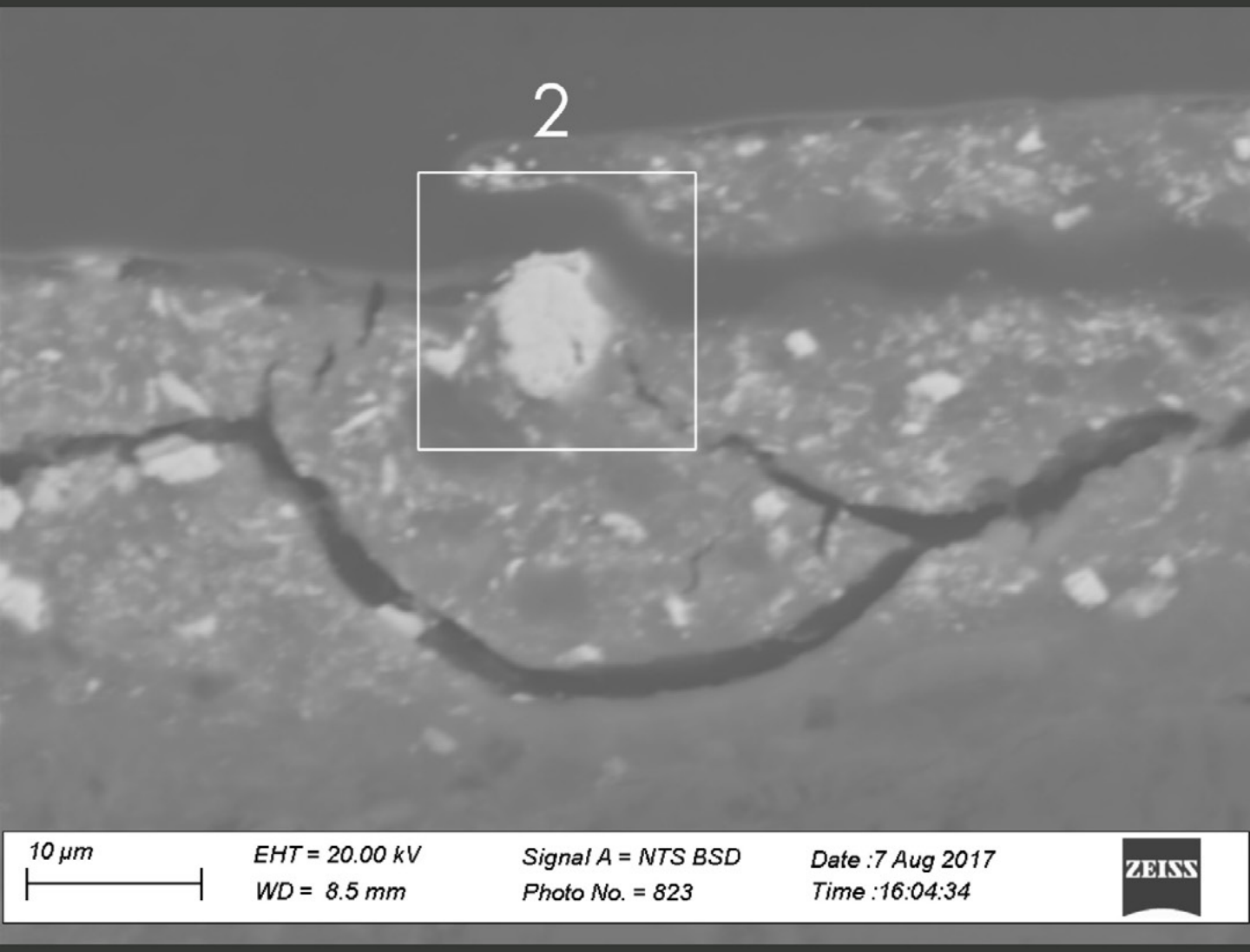
Location: Highlight from Saint Andrew's garment, after treatment

GROUND LAYERS

Only a portion of the upper ground was retained during sampling. The upper ground contains an even distribution of aluminosilicates, chalk, and potassium. A large semitransparent particle (3) containing only silicon and oxygen is present in the lower ground.

PAINT LAYERS

SEM-EDS maps confirm that the larger red particles in the red paint layer (b) correspond to the mercury maps confirming the presence of vermilion. An EDS point scan of particle 2 indicates peaks for mercury and sulfur, identifying the particle as vermilion (mercury sulfide). Both the large bright white and smaller, slightly gray particle (1), as seen in normal light, are composed of lead white; see the EDS map for lead. An EDS point scan among the smaller red and white particles within the red paint layer reveal the presence of mercury and lead, indicating that the more finely ground pigments below particle 2 are also composed of the lead white and vermilion.



10 µm

EHT = 20.00 kV
WD = 8.5 mm

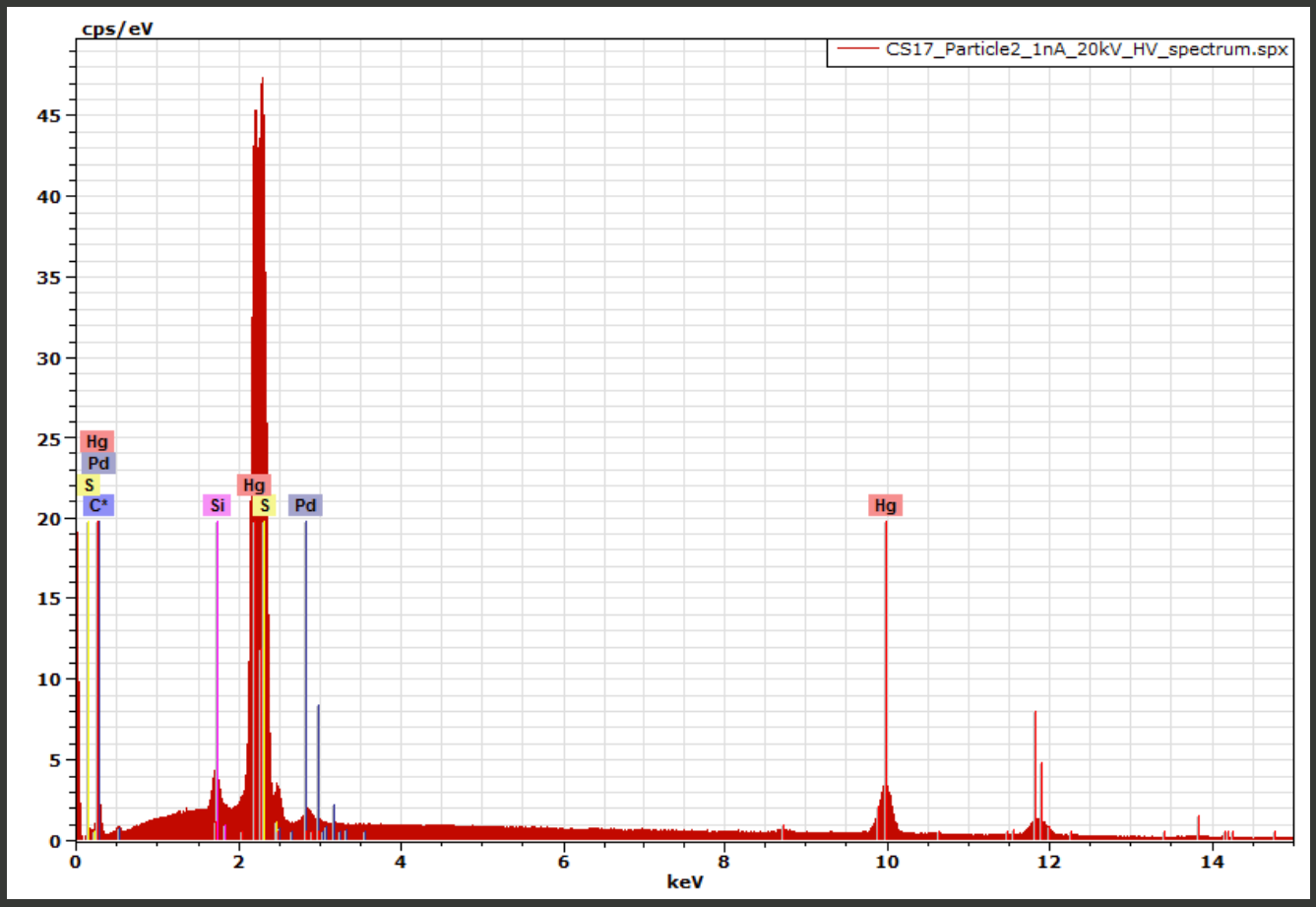
Signal A = NTS BSD
Photo No. = 823

Date :7 Aug 2017
Time :16:04:34

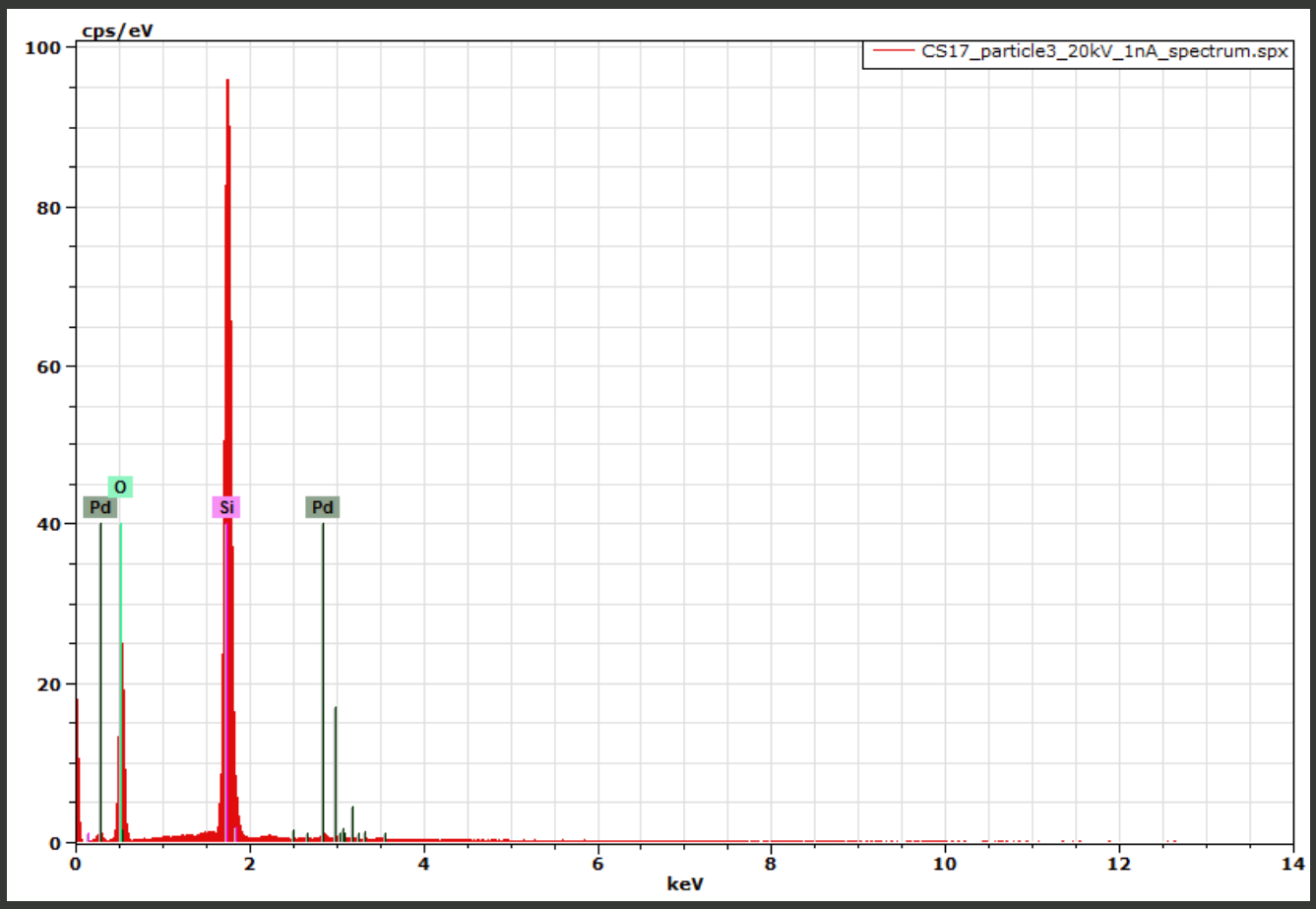
ZEISS

Cross Section 17 (CS17)

Location: Highlight from Saint Andrew's garment, after treatment



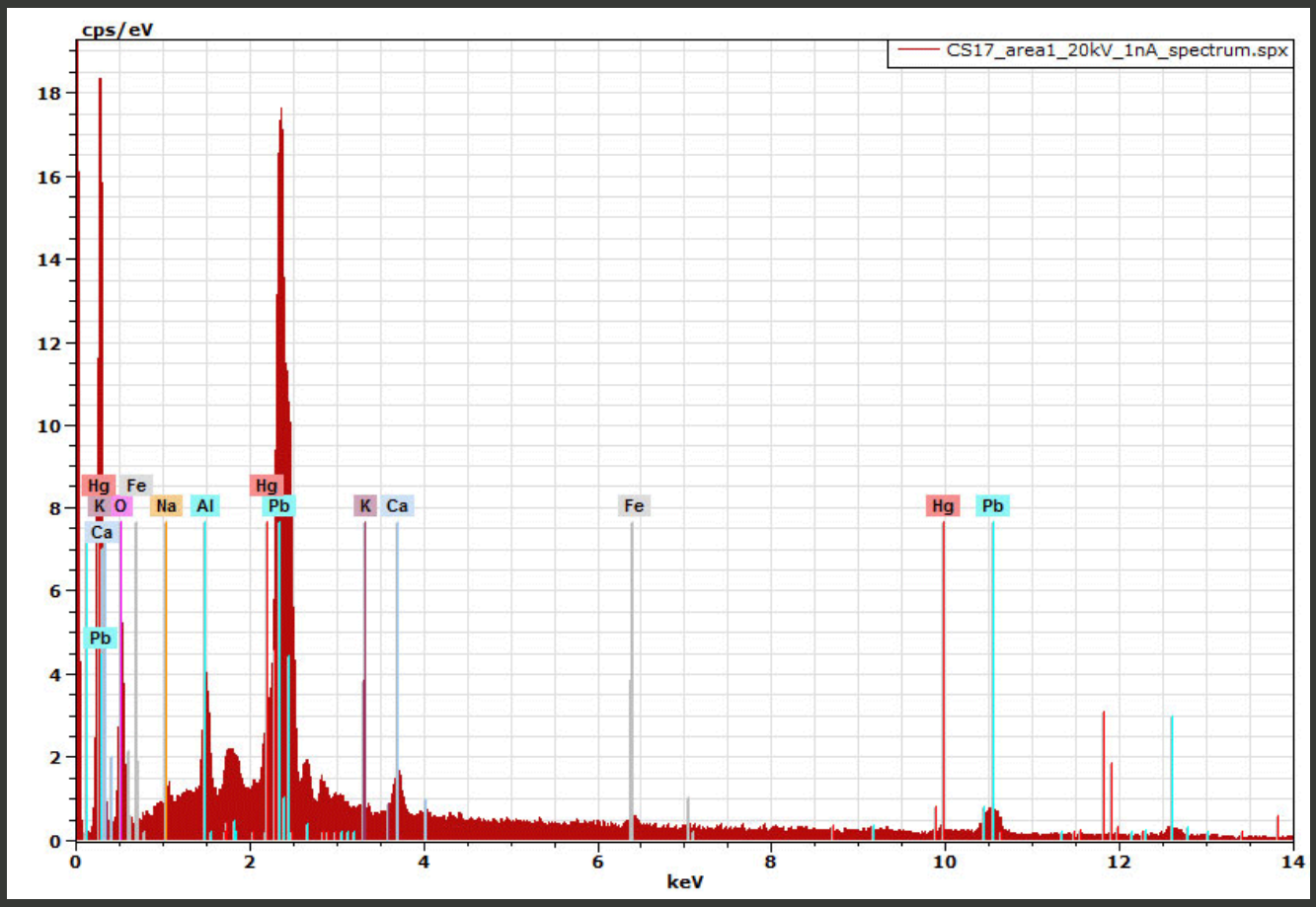
EDS spectrum for particle 2 (vermilion). This sample was coated with palladium to reduce electron charging, accounting for the palladium peaks.



EDS spectrum for particle 3. This sample was coated with palladium to reduce electron charging, accounting for the palladium peaks.

Cross Section 17 (CS17)

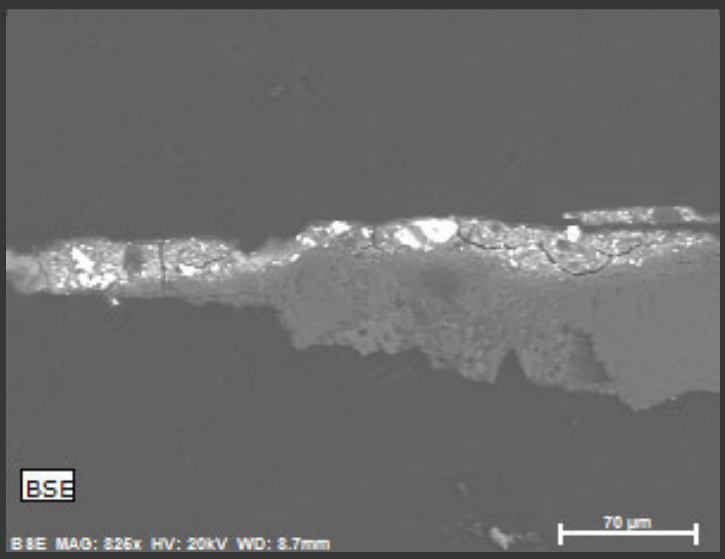
Location: Highlight from Saint Andrew's garment, after treatment



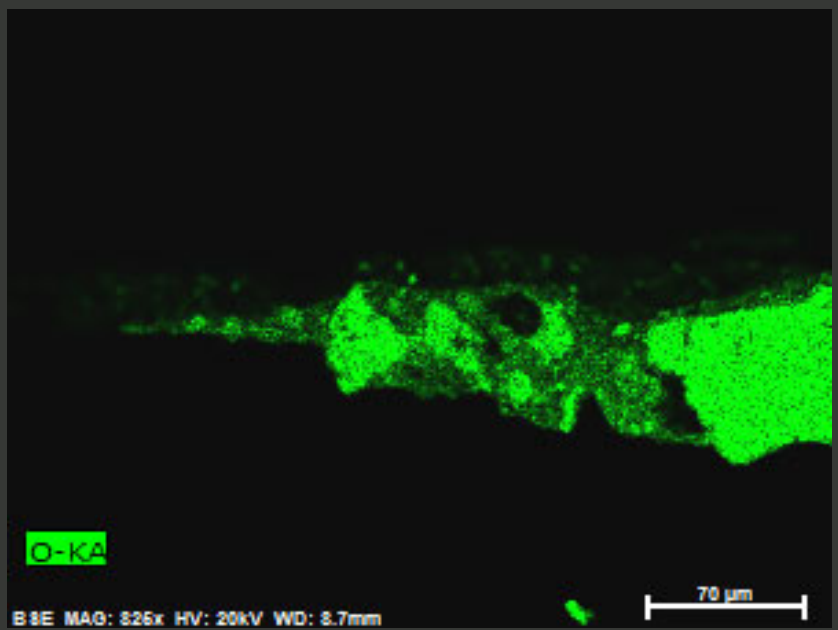
EDS spectrum for particles below particle 2. This sample was coated with palladium to reduce electron charging, accounting for the palladium peaks.

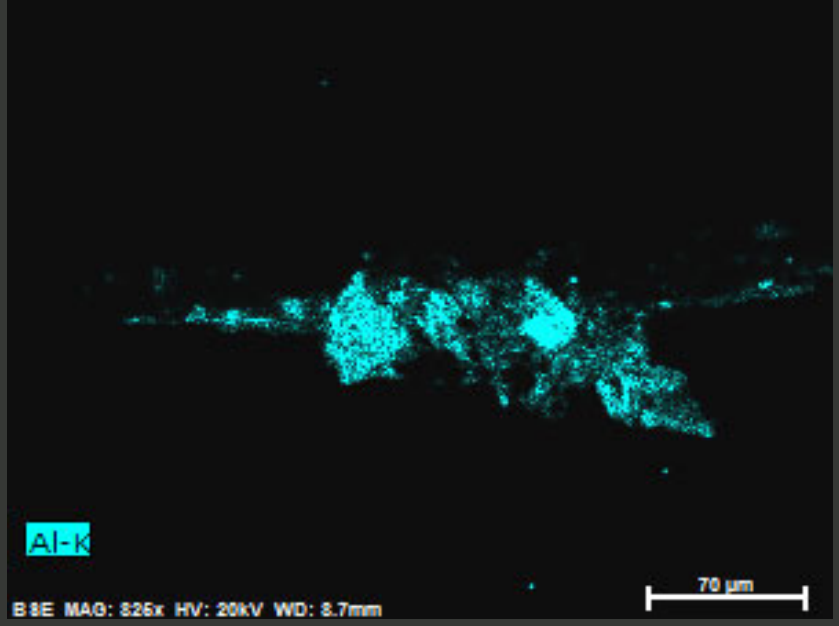
SEM-EDS MAPS

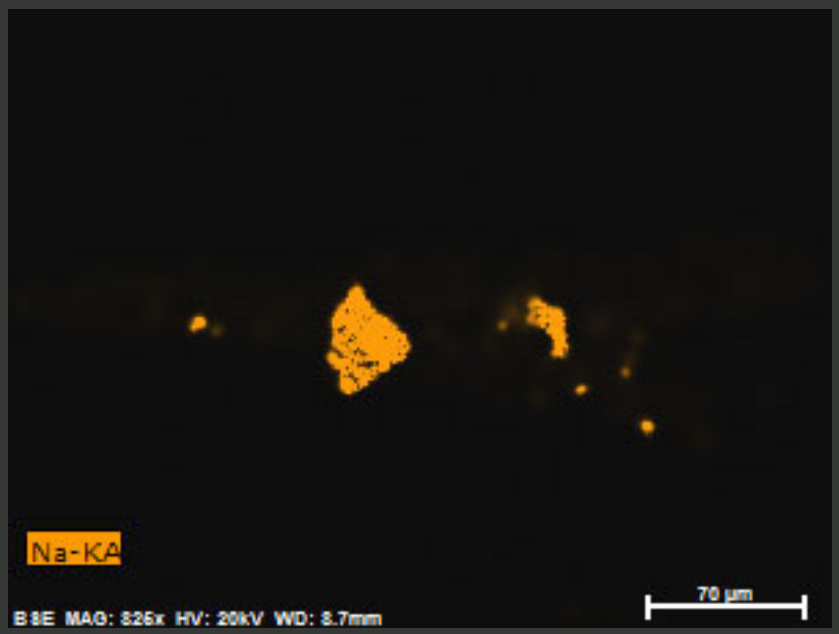
BSE
O
Na
Mg
Al
Si
P
S
K
Ca
Mn
Fe
Hg
Pb

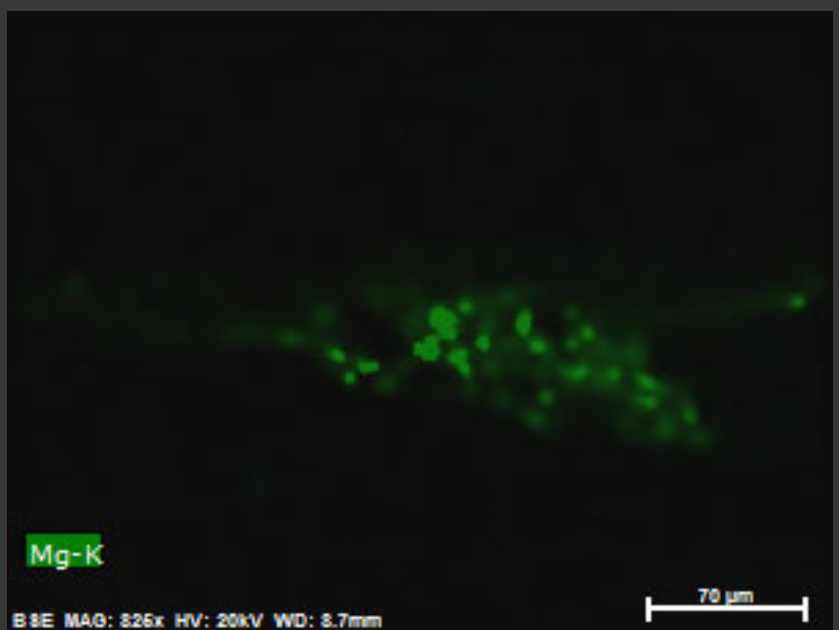


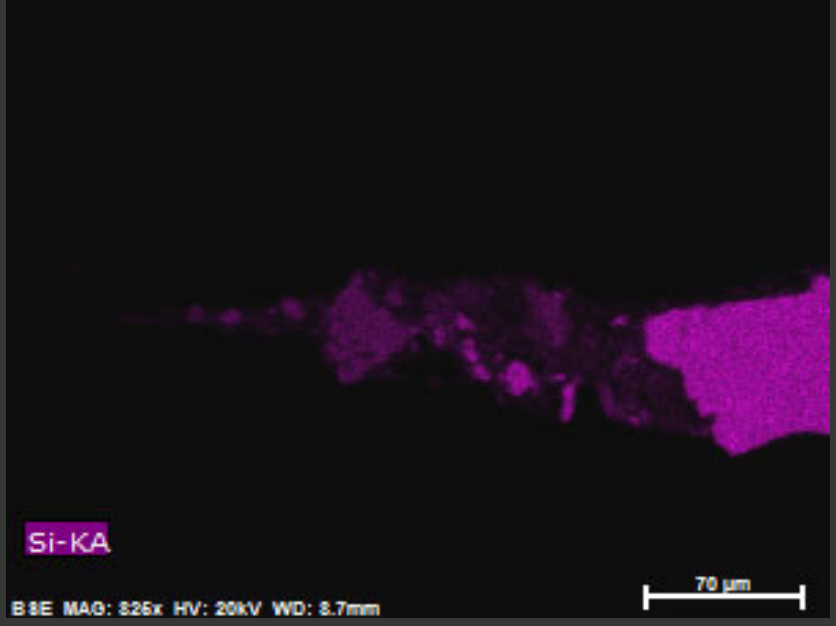
MAG: 825x
HV: 20 kV
WD: 8.7 mm
Scale bar: 70 µm

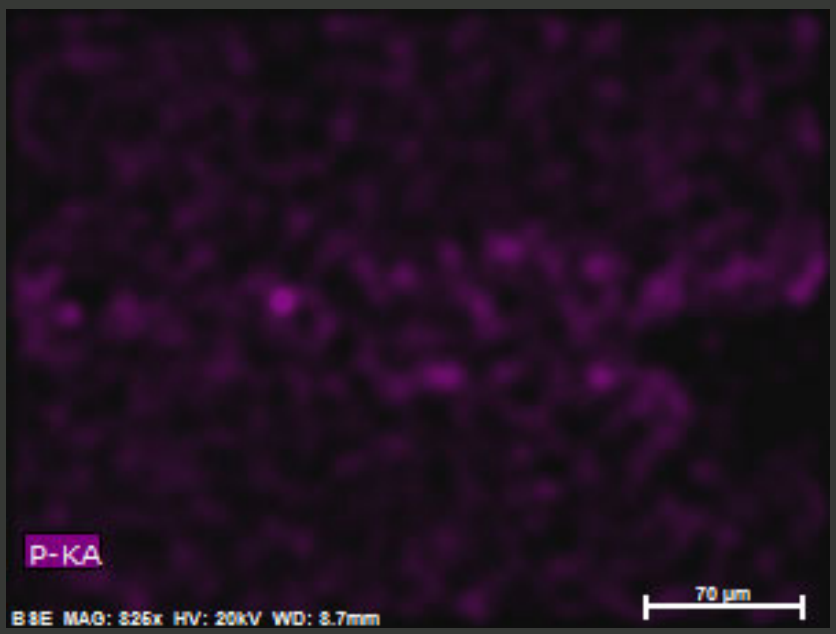


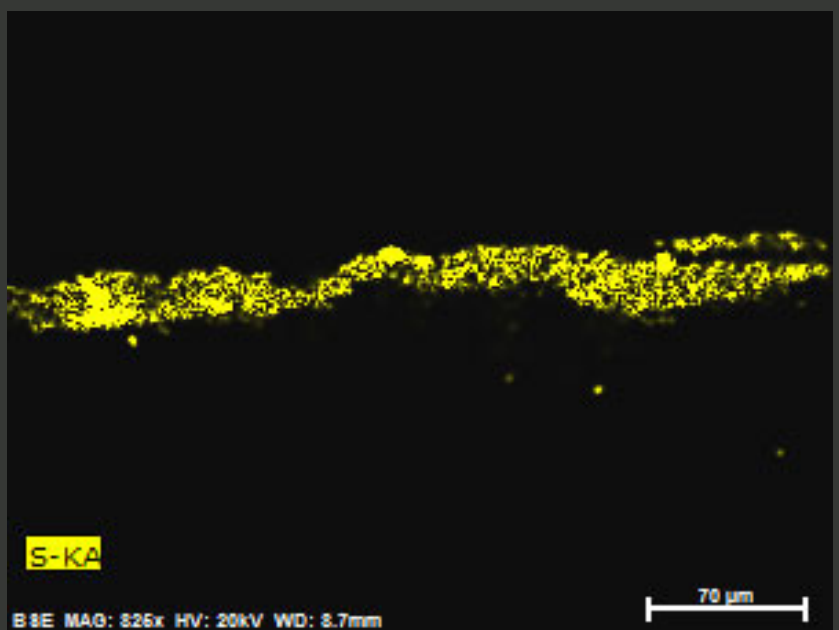

Al-K
B 8E MAG: 826x HV: 20kV WD: 8.7mm
70 µm

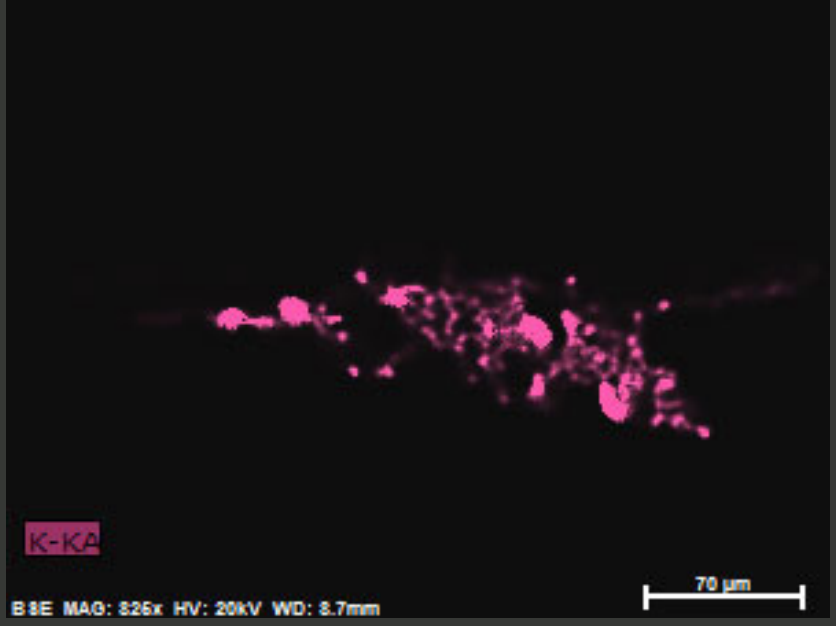

Na-KA
B 8E MAG: 826x HV: 20kV WD: 8.7mm
70 µm

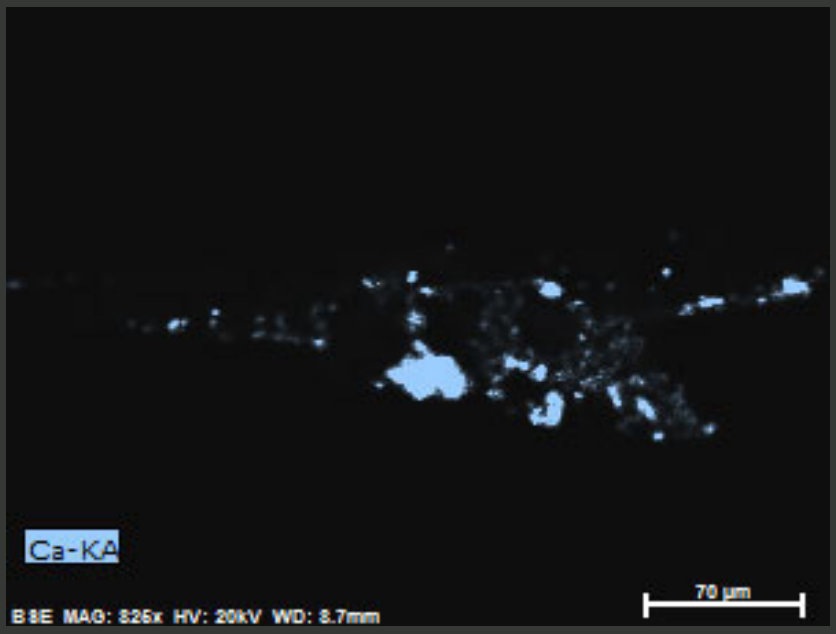

Mg-K
B 8E MAG: 826x HV: 20kV WD: 8.7mm
70 µm

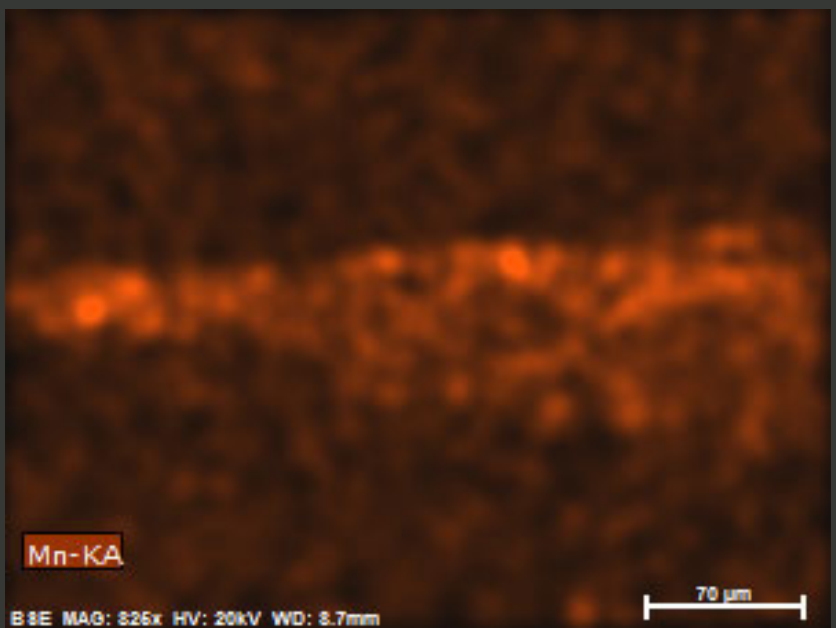

Si-KA
70 µm
B 8E MAG: 826x HV: 20kV WD: 8.7mm


P-KA
70 µm
B 8E MAG: 826x HV: 20kV WD: 8.7mm

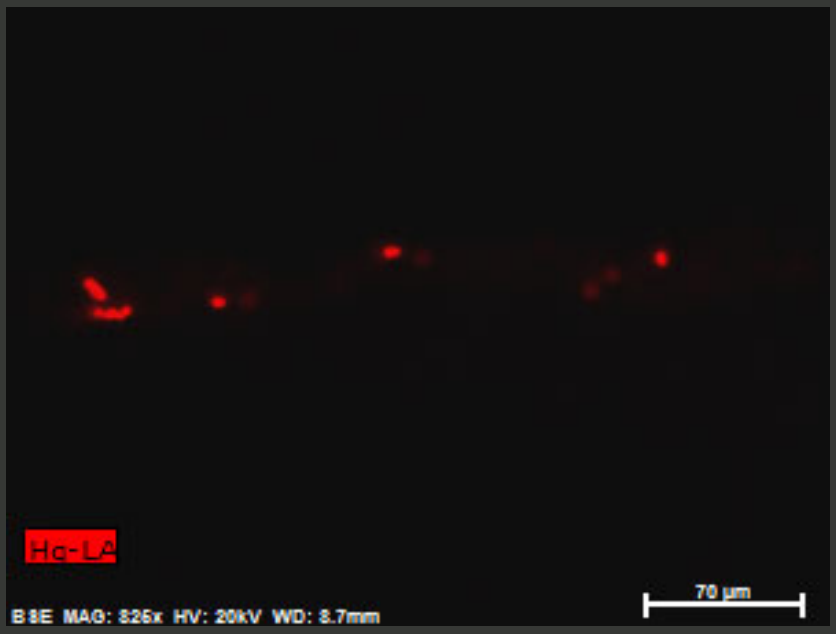

S-KA
70 µm
B 8E MAG: 826x HV: 20kV WD: 8.7mm

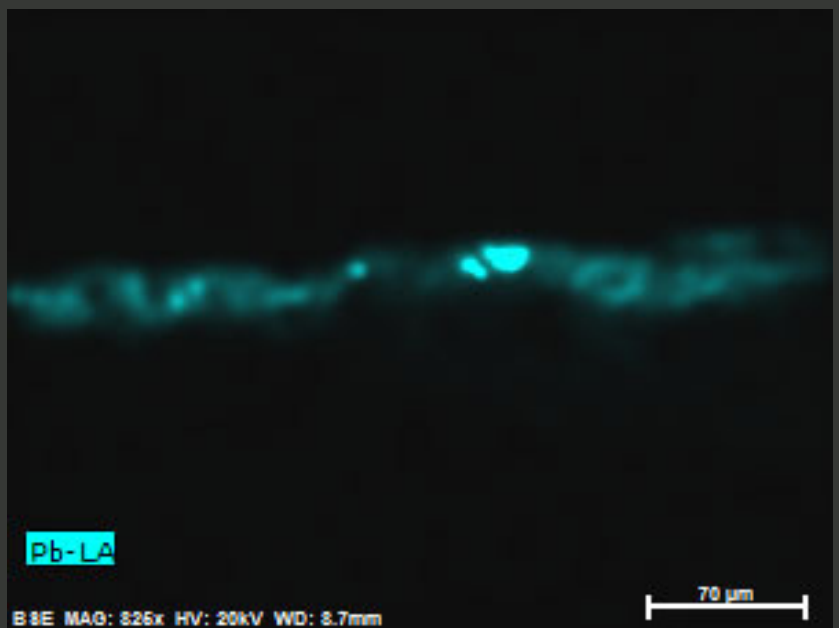

K-KA
70 µm
B SE MAG: 826x HV: 20kV WD: 8.7mm

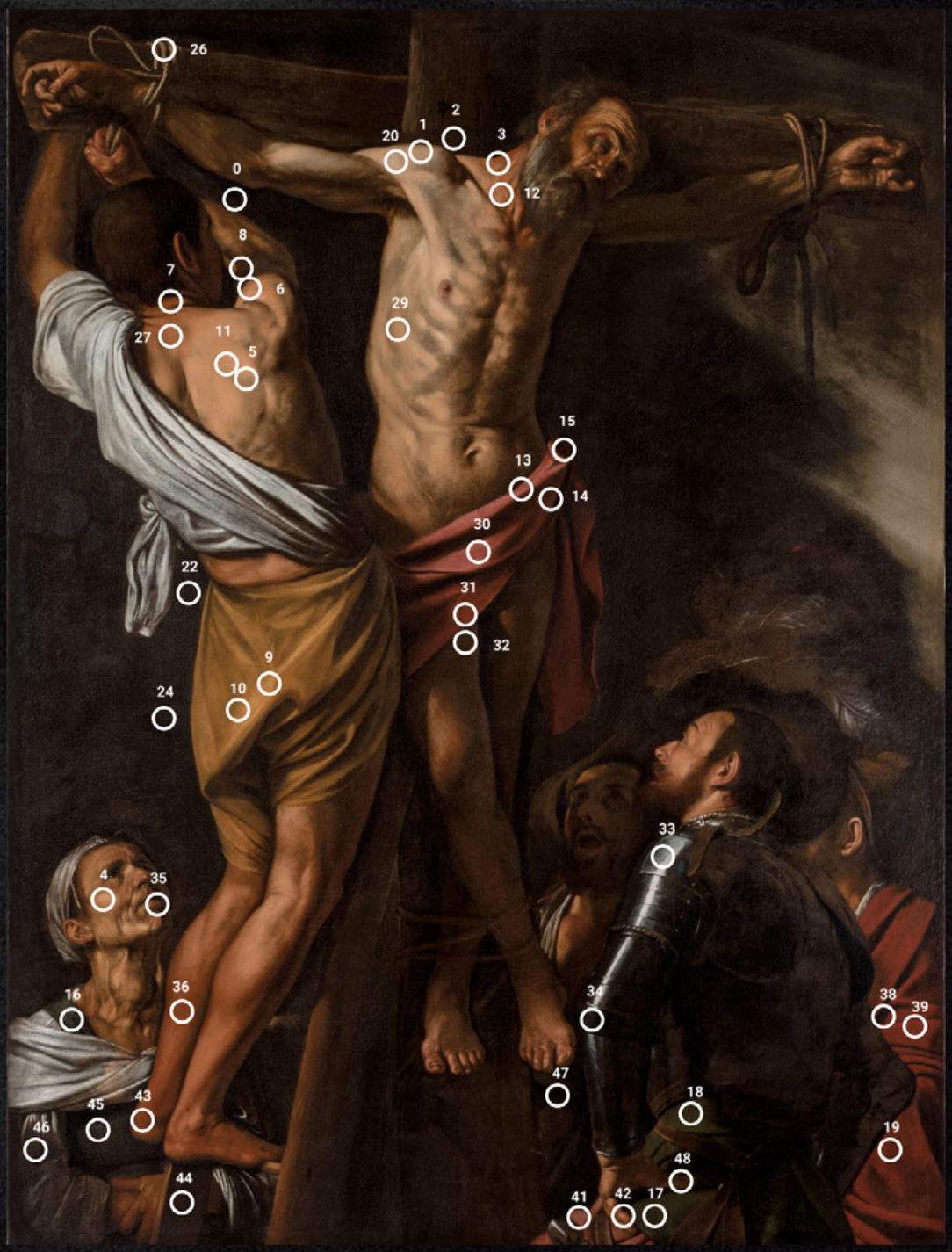

Ca-KA
70 µm
B SE MAG: 826x HV: 20kV WD: 8.7mm


Mn-KA
70 µm
B SE MAG: 826x HV: 20kV WD: 8.7mm

Fe-KA
70 µm
B SE MAG: 826x HV: 20kV WD: 8.7mm


Hg-LA
70 µm
B SE MAG: 826x HV: 20kV WD: 8.7mm


Pb-LA
70 µm
B SE MAG: 826x HV: 20kV WD: 8.7mm



Introduction to XRF Analysis

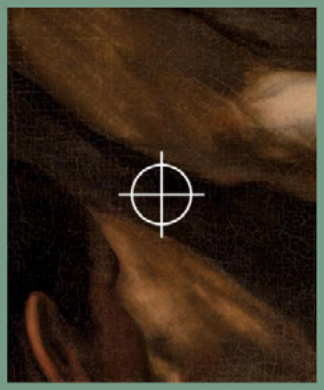
Introduction to XRF Analysis

X-ray fluorescence spectroscopy (XRF) is a nondestructive way to identify elements in a material by producing a narrow beam of X-ray photons that interacts with atoms in a sample. Each element present in the sample has a characteristic electron structure. The X-ray beam ejects an inner shell electron from an atom, at which point an electron from an outer orbital fills the hole, resulting in the release of characteristic X-ray radiation in the form of a fluoresced photon to stabilize the atom. Elements with multiple electron shells (transition metals and heavy metals) can reveal numerous characteristic x-ray energies. The XRF detector measures the energies of these characteristic X-rays to create a fluorescence spectrum. The spectrum of emitted x-ray energies can be interpreted by scientists and conservators to identify the elements that are present.

Although XRF is a powerful analytical technical, it does not detect pigments specifically, but rather suggests certain pigments by the elements that are detected. Metal filters can be placed in front of the beam to remove undesirable background radiation. The CMA's handheld XRF has an X-ray tube with a rhodium (Rh) target that produces energies at 2.697 keV (Rh Lα) and 20.216 keV (Rh Kα). Trace peaks of nickel (Ni) associated with the detector may also appear in the spectra. Therefore, unless filtered, peaks associated with the elements rhodium and nickel usually appear in the spectrum but are not always marked. Also, some gaps in the numerical order of the XRF locations are present, since the data collected from these areas was considered to be less reliable.

Location 0

Area of exposed ground at the upper left



Notes / possible pigments

Ochre pigments; aluminosilicates; chalk; trace of umber, bone black, lead white

Major intensity	Minor intensity	Trace intensity
Calcium (Ca)	Manganese (Mn)	Aluminum (Al)
Iron (Fe)	Potassium (K)	Copper (Cu)
	Silicon (Si)	Lead (Pb)
		Phosphorus (P)
		Titanium (Ti)

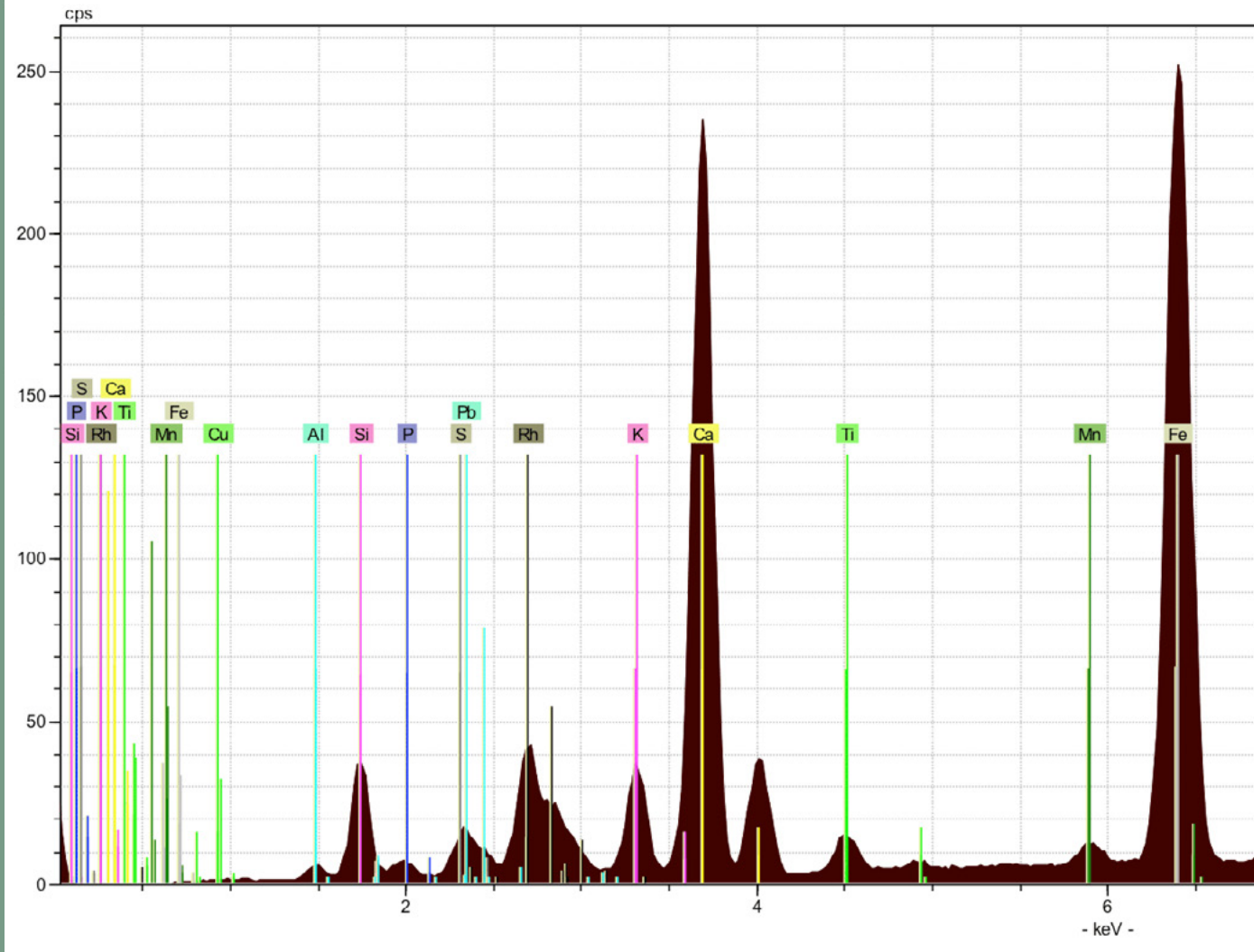
15 kV

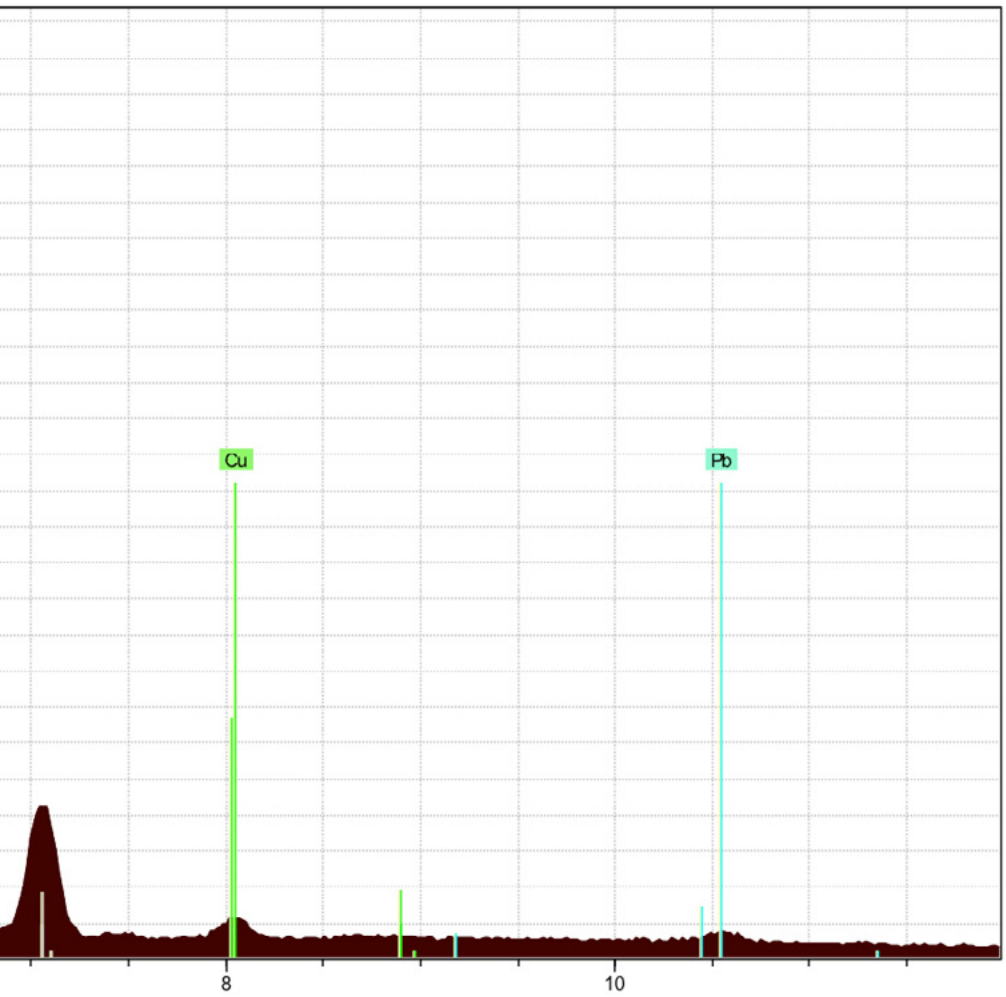
10 µA

air

filter: no

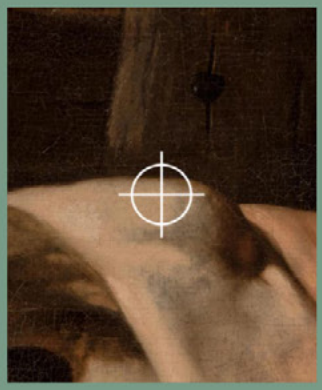
time: 60 seconds




Cu
Pb
8
10

Location 1

Saint Andrew's shoulder



Notes / possible pigments

Lead white; ochre pigments

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)

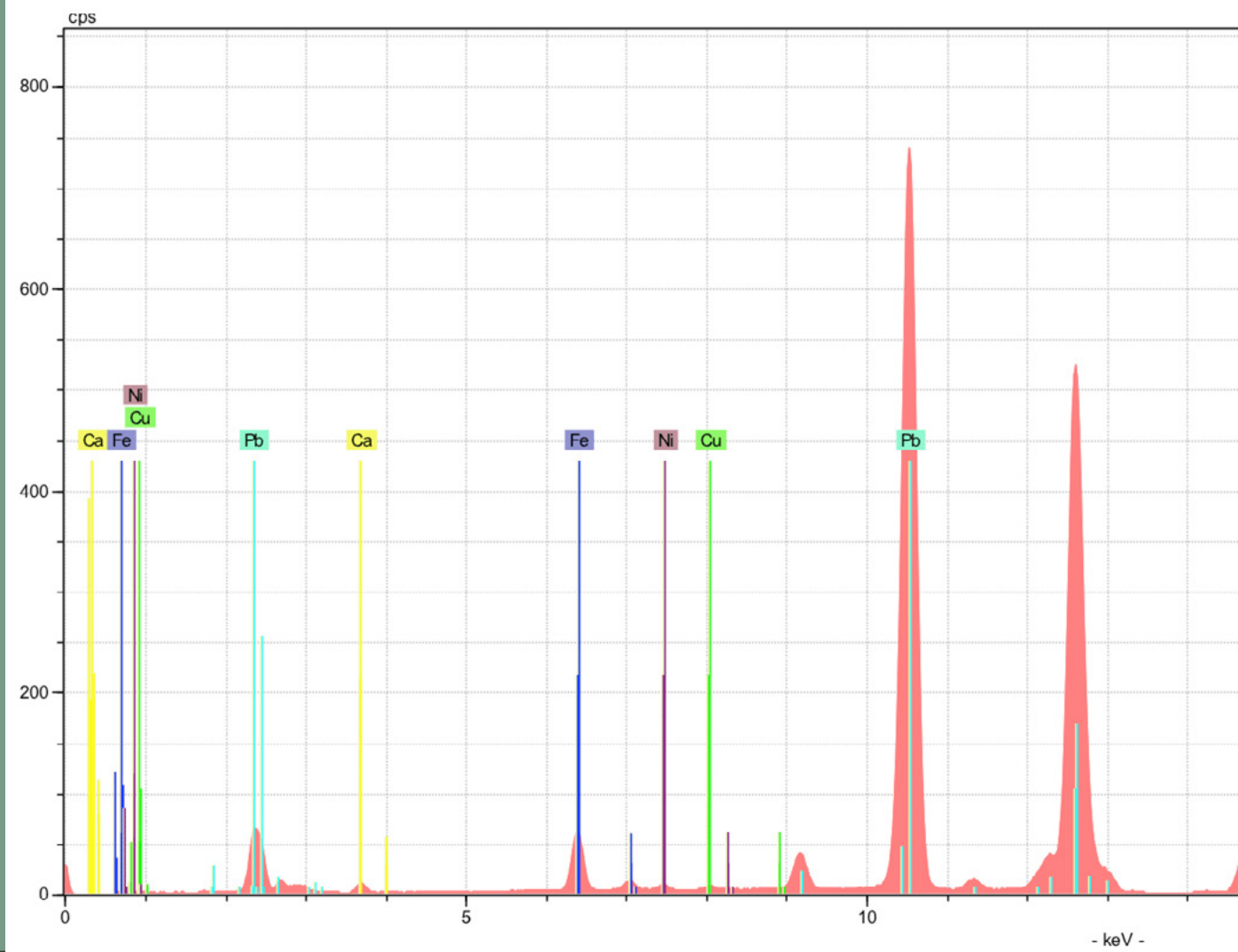
40 kV

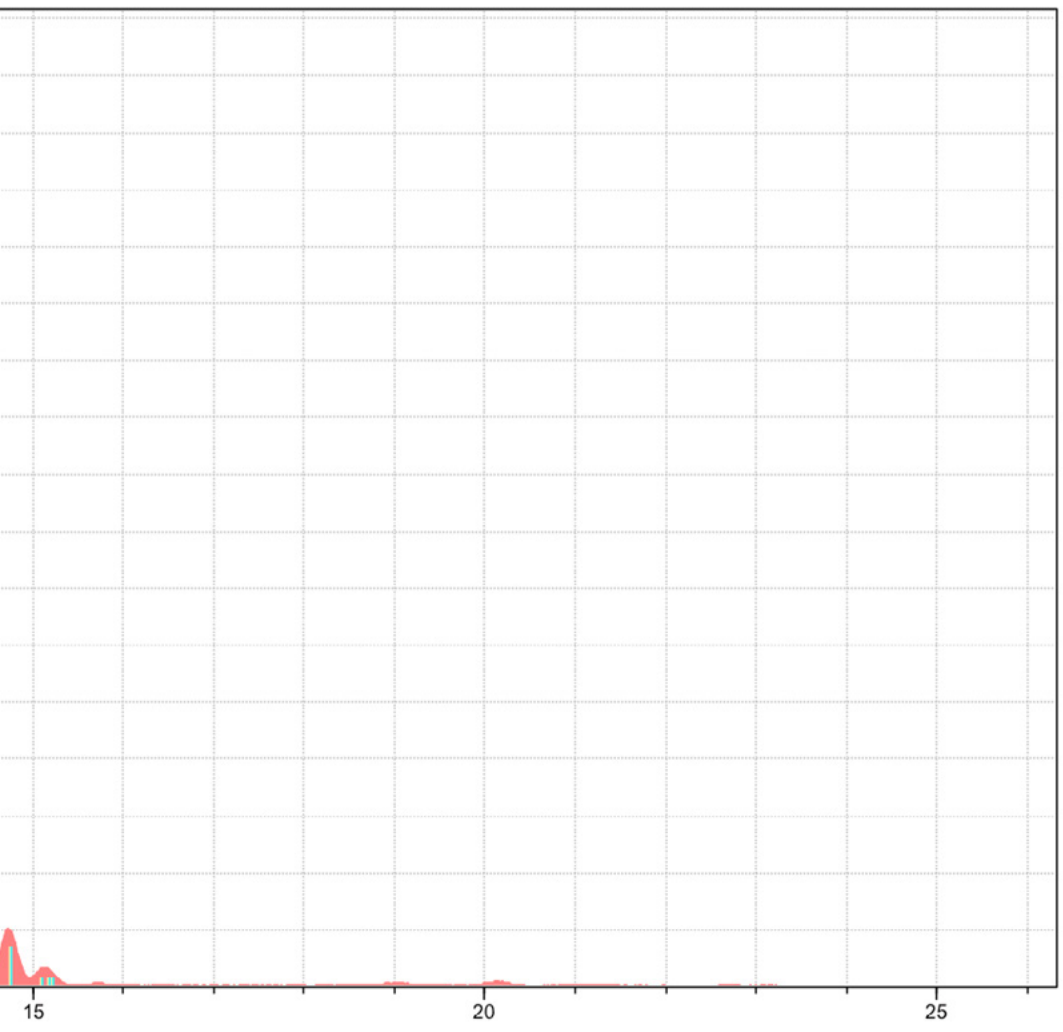
1.8 µA

air

filter: no

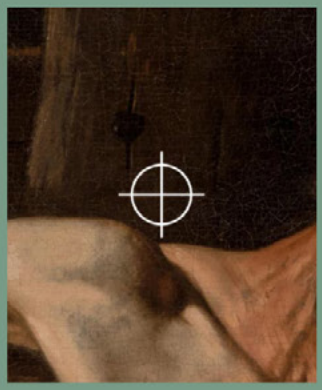
time: 120 seconds




15
20
25

Location 2

The cross above Saint Andrew's shoulder

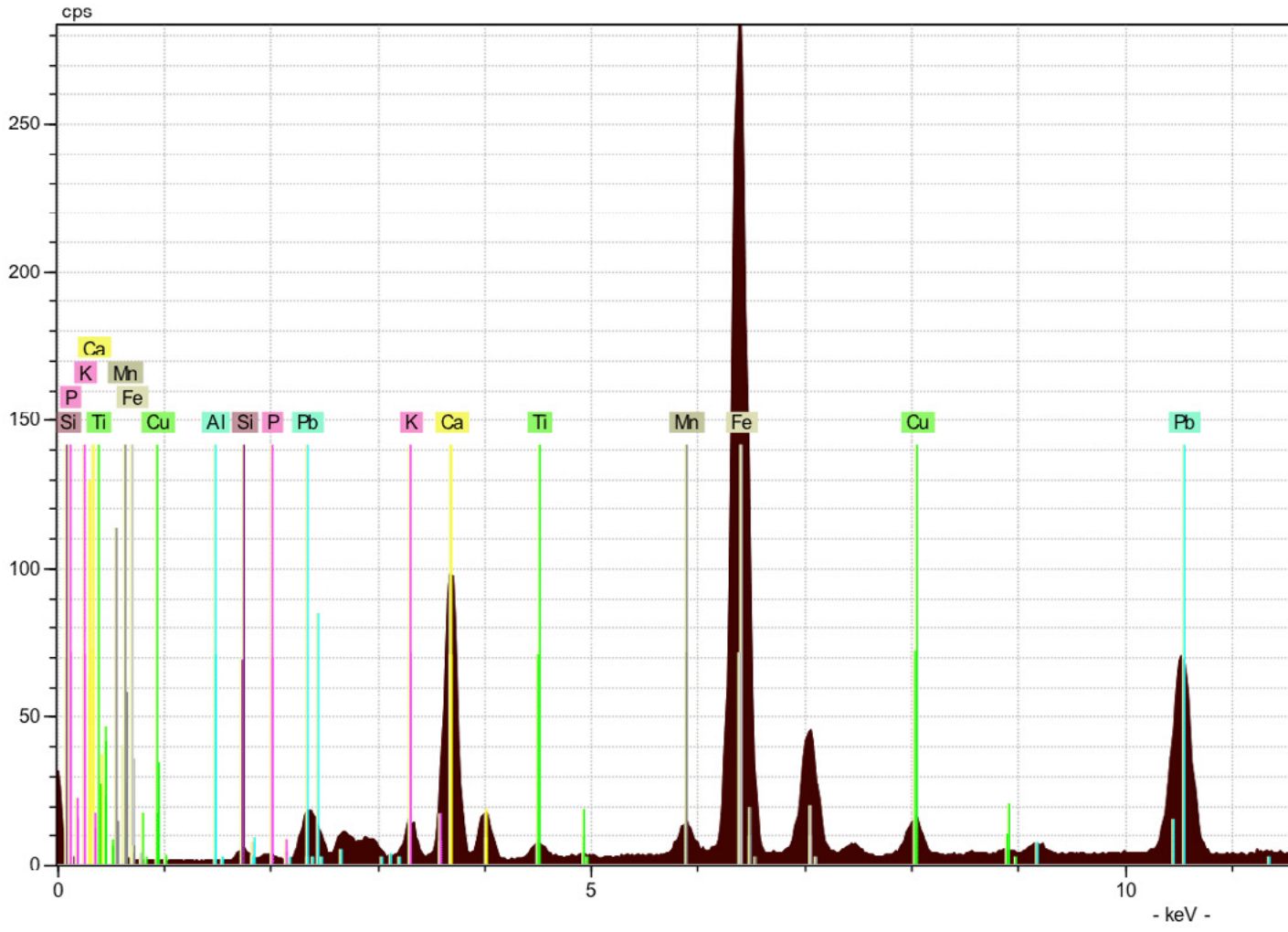


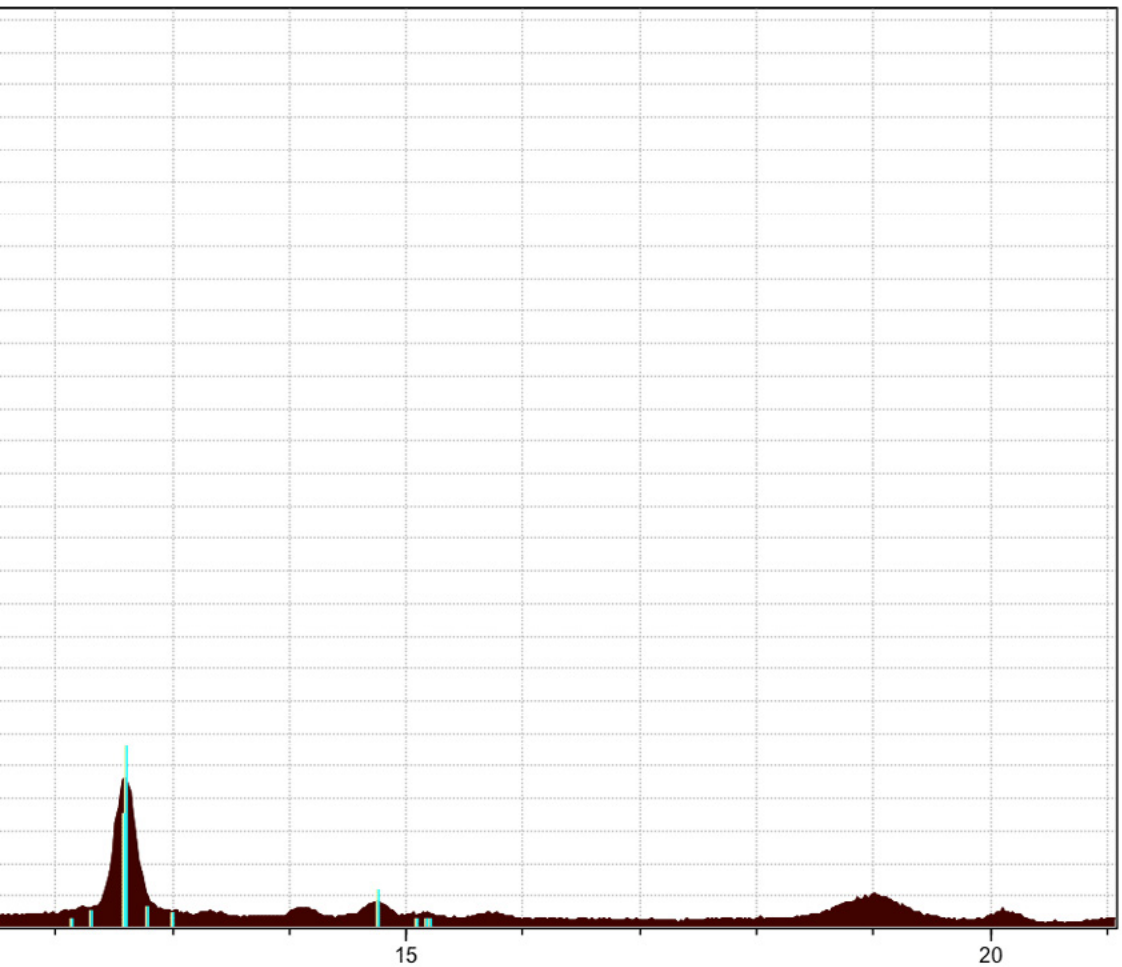
Notes / possible pigments

Ochre pigments; umber; bone black;
copper-based pigment; lead white; chalk

Major intensity	Minor intensity	Trace intensity
Iron (fe)	Calcium (Ca)	Copper (Cu)
	Lead (Pb)	Phosphorus (P)
	Manganese (Mn)	Silicon (Si)
	Potassium (K)	Titanium (Ti)

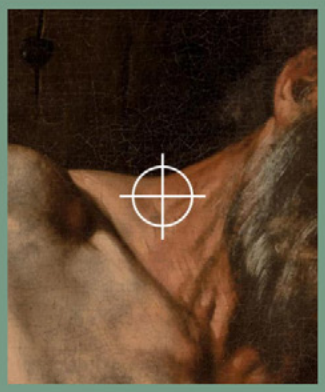
40 kV
1.8 µA
air
filter: no
time: 60 seconds




15
20

Location 3

Red area of Saint Andrew's neck



Notes / possible pigments

Lead white; ochre pigments; vermilion

Major intensity	Trace intensity
Iron (Fe)	Calcium (Ca)
Lead (Pb)	

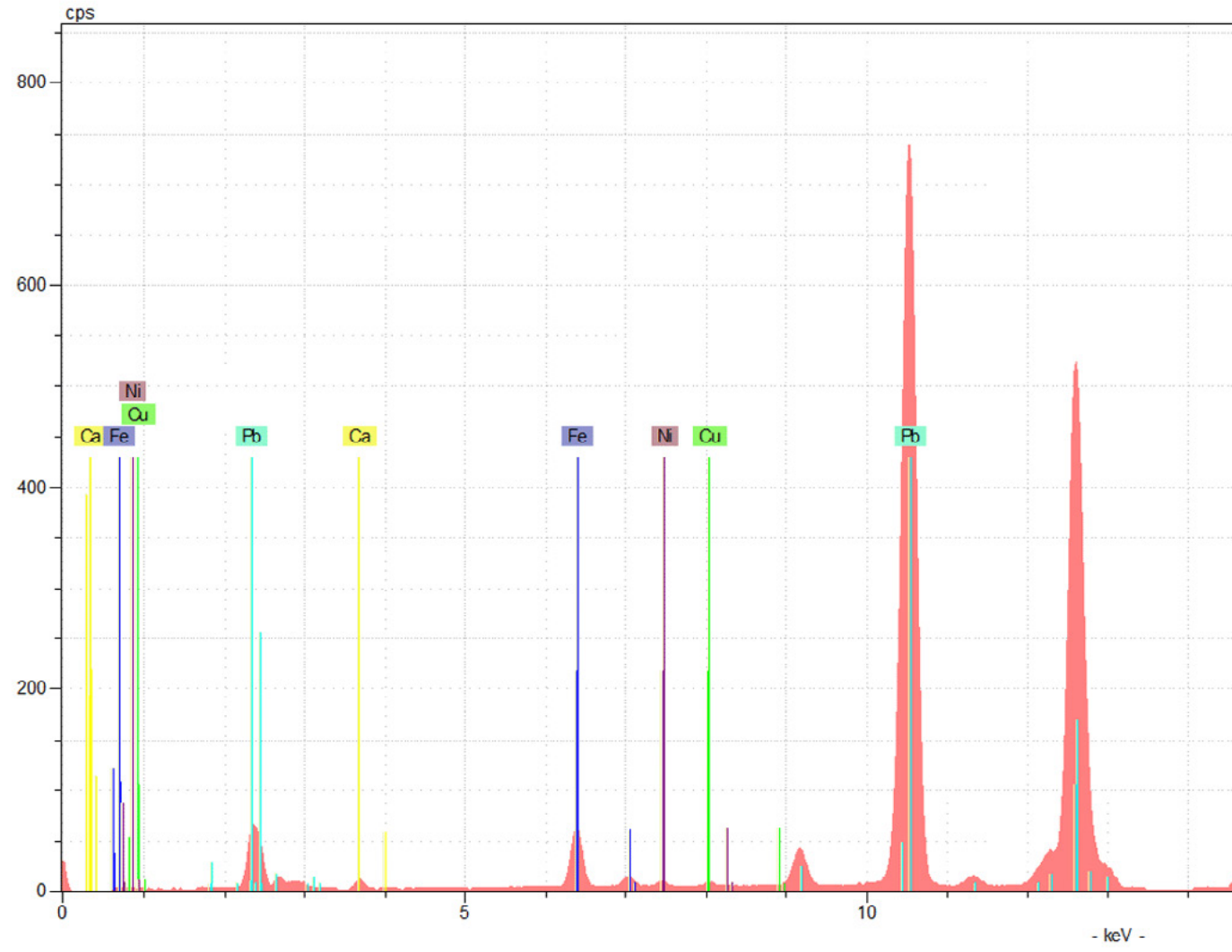
40 kV

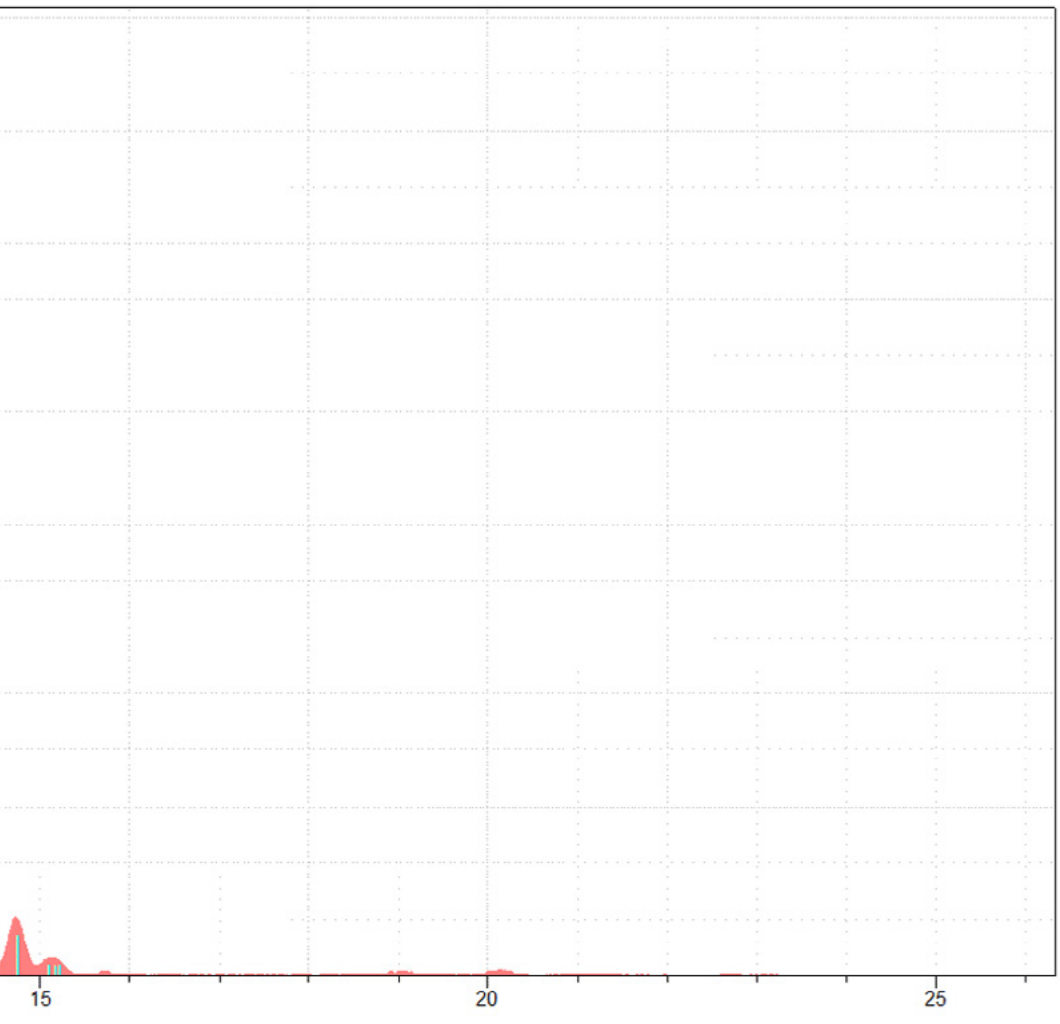
1.8 µA

air

filter: no

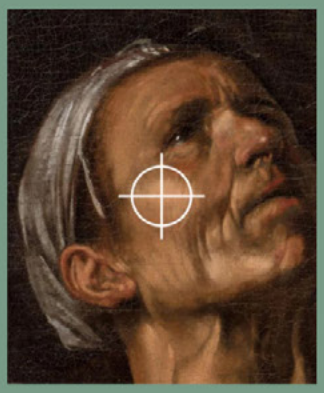
time: 60 seconds




15
20
25

Location 4

Old woman's face, highlight on cheek



Notes / possible pigments

Lead white; ochre pigments; chalk

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)

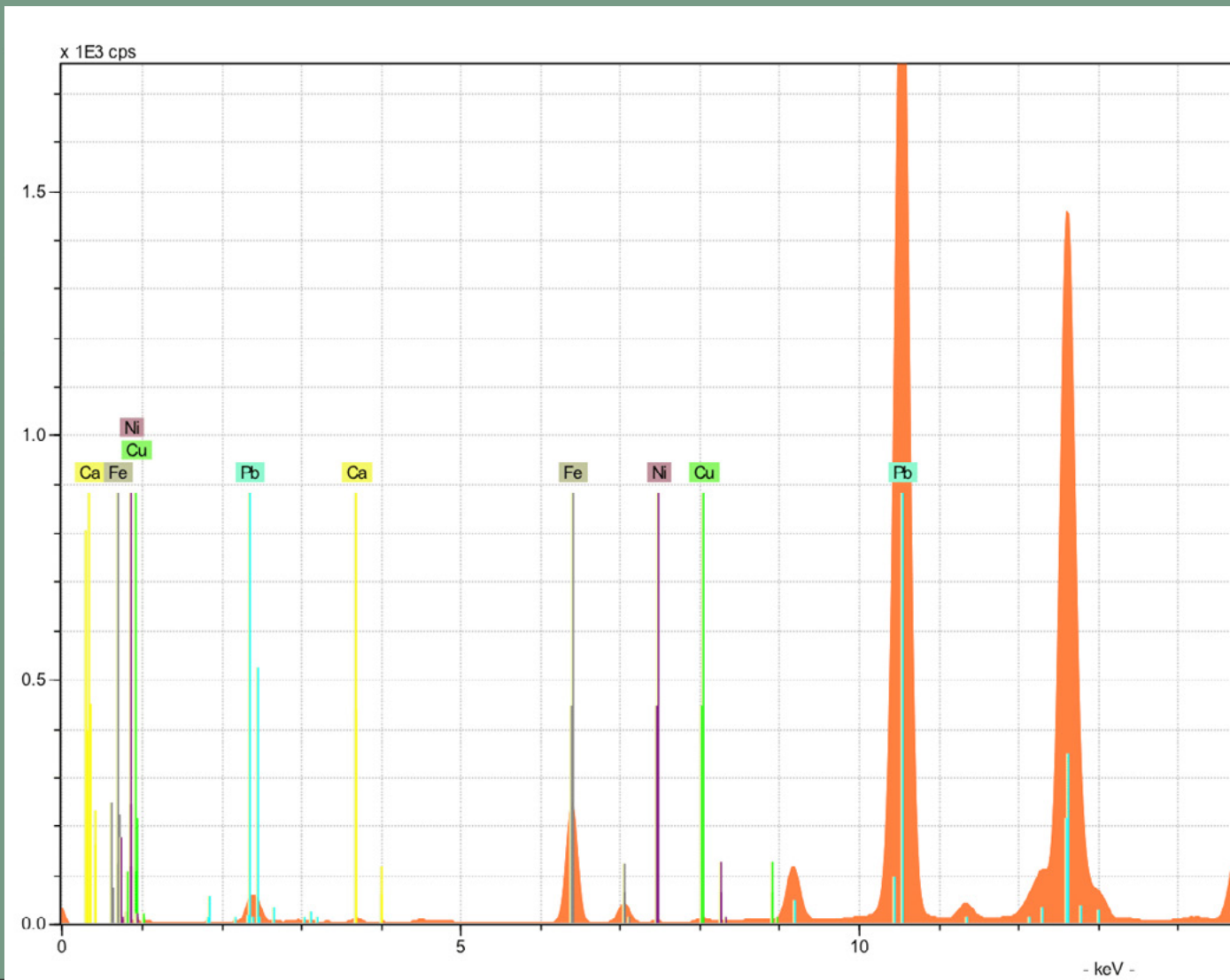
40 kV

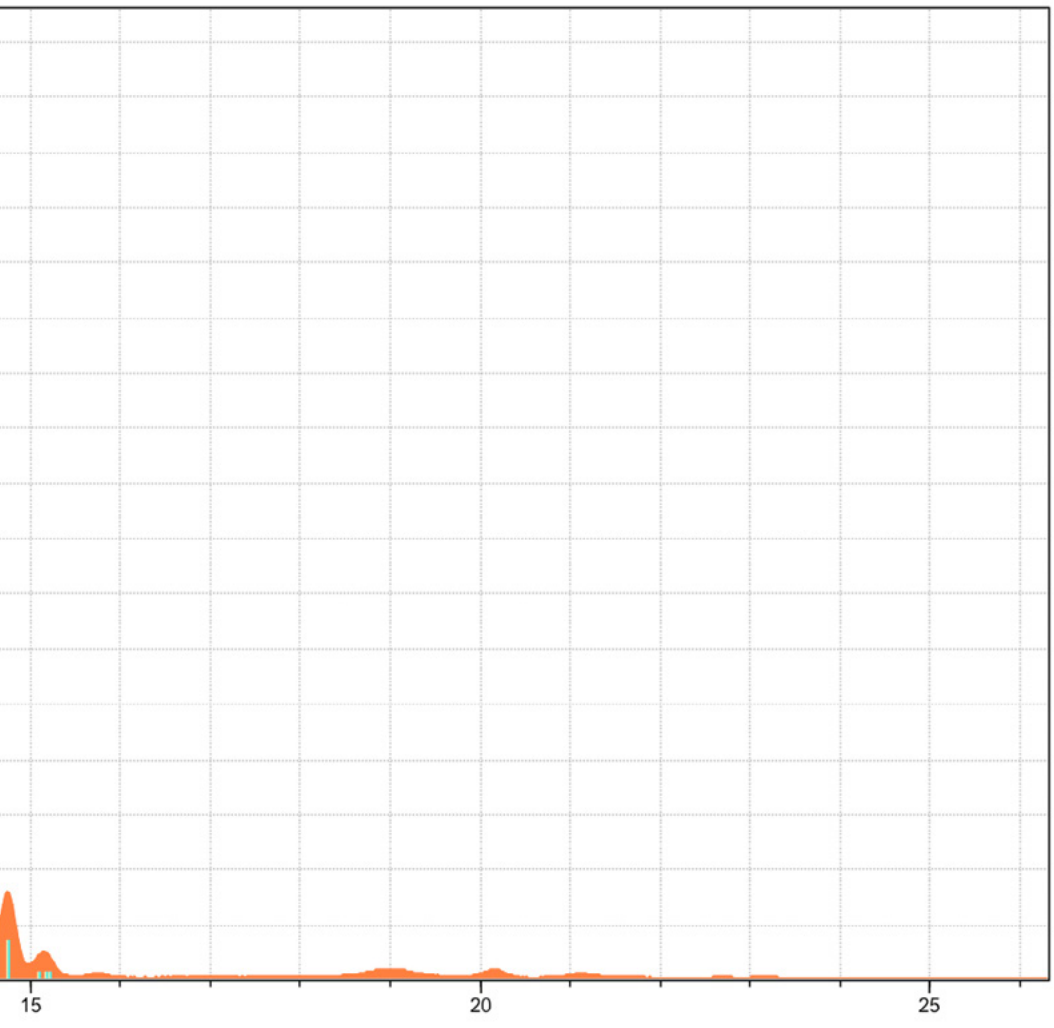
10 µA

air

filter: Ti 1 mil foil

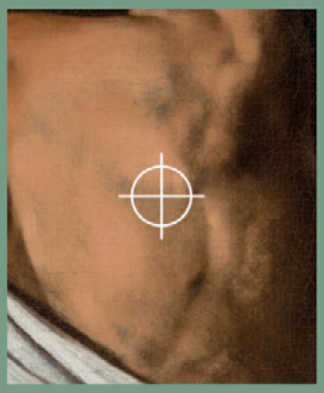
time: 180 seconds




15
20
25

Location 5

Highlight on the back of the executioner on the ladder



Notes / possible pigments

Lead white; ochre pigments

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Copper (Cu)

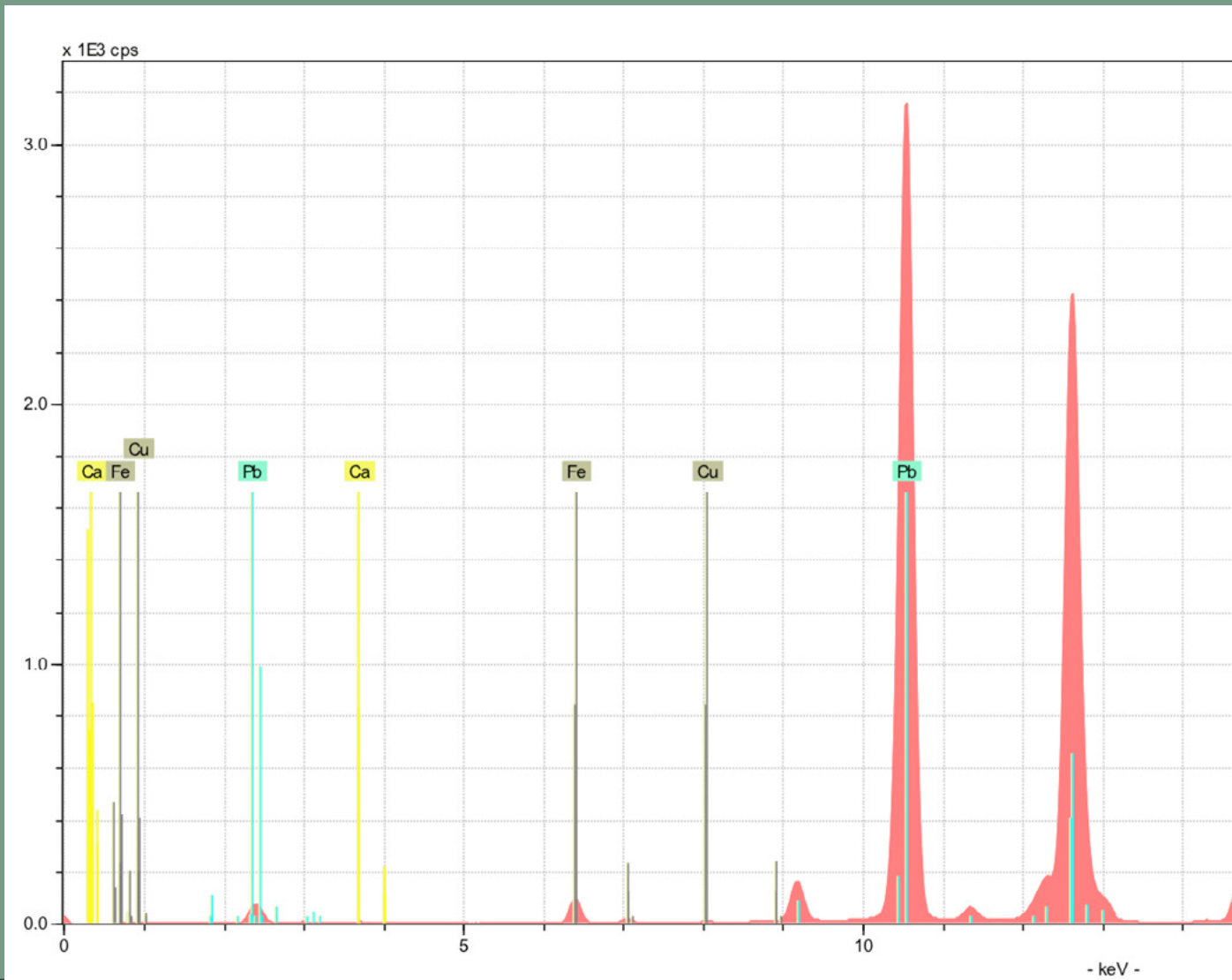
40 kV

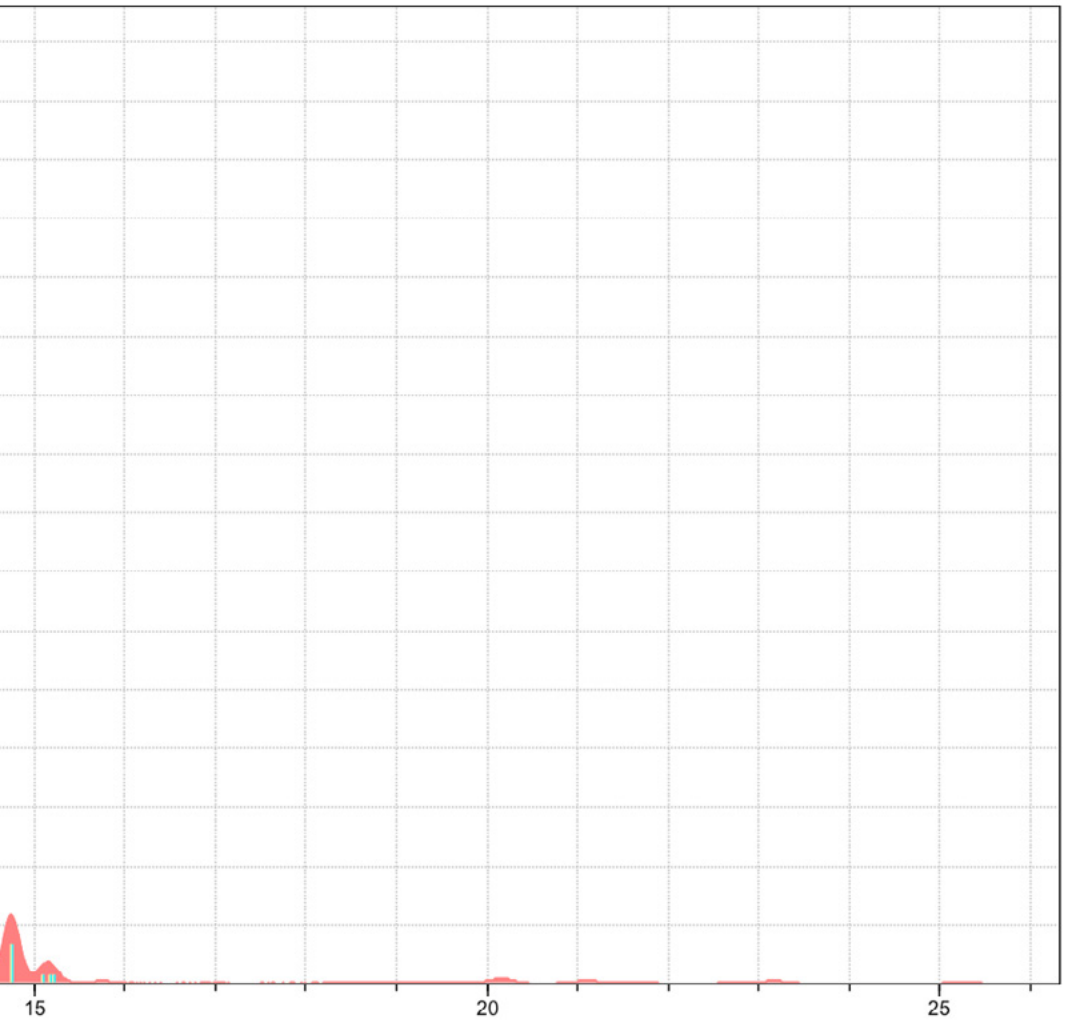
10 µA

air

filter: Ti 1 mil foil

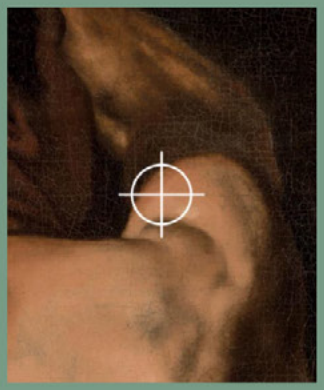
time: 180 seconds




15
20
25

Location 6

Edge of the reddish shadow of the deltoid muscle of the executioner on the ladder



Notes / possible pigments

Lead white; ochre pigments; chalk

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)

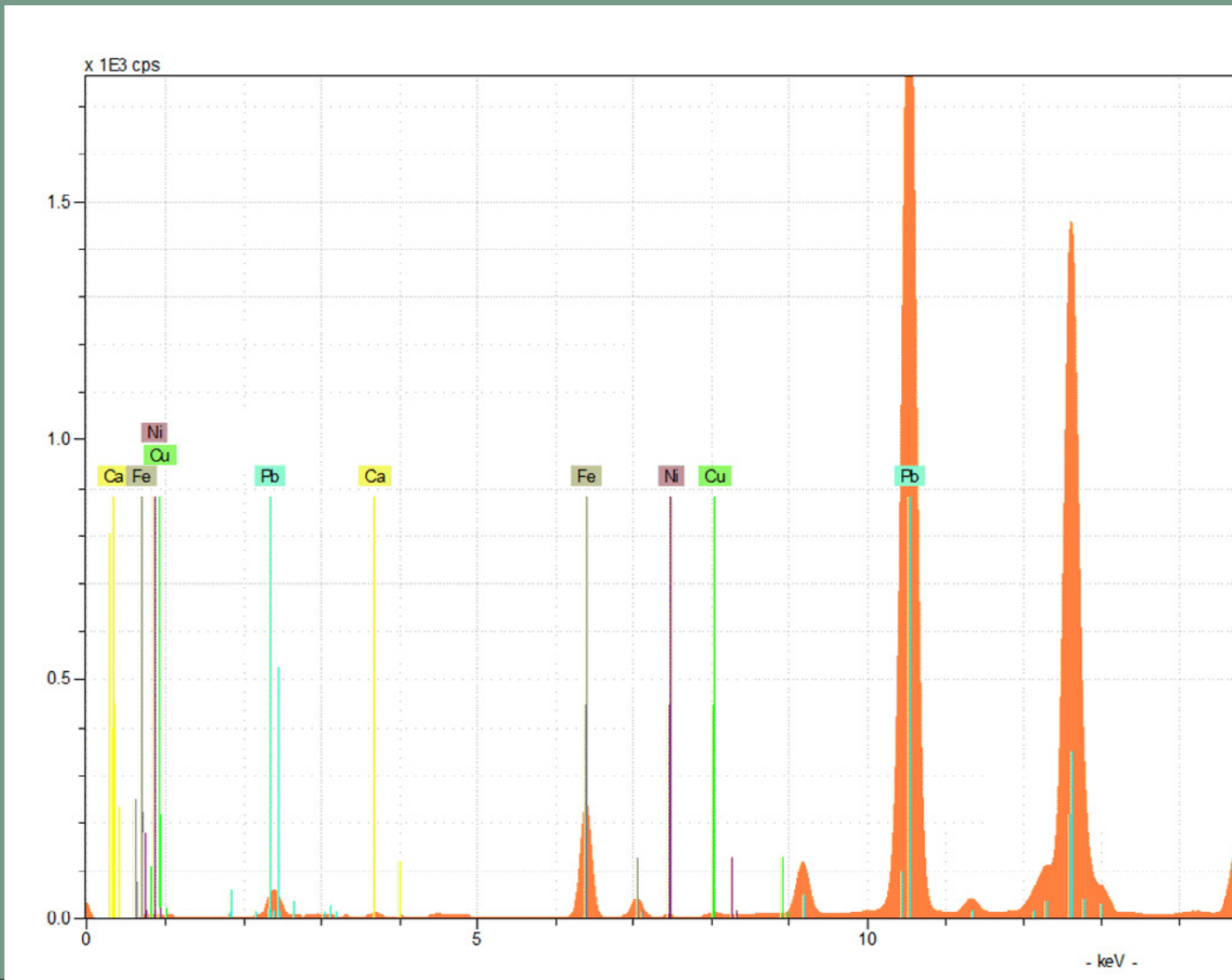
40 kV

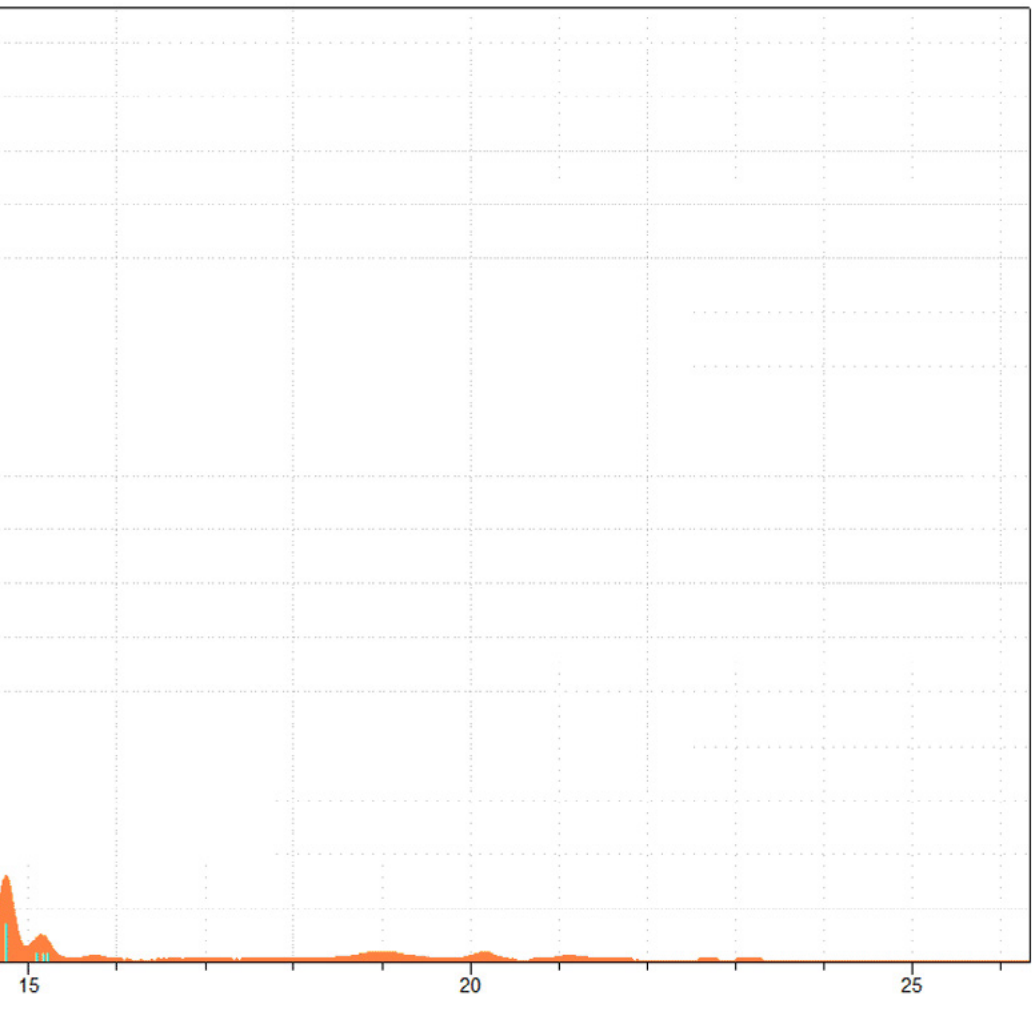
10 µA

air

filter: Ti 1 mil foil

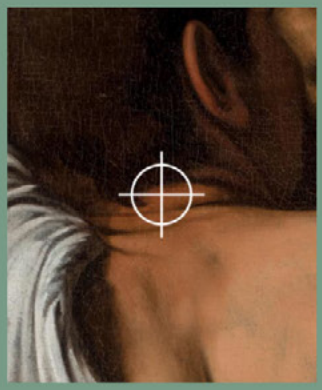
time: 180 seconds




15
20
25

Location 7

Edge of the reddish shadow of the neck of the executioner on the ladder



Notes / possible pigments

Lead white; ochre pigments; chalk

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)
		Copper (Cu)

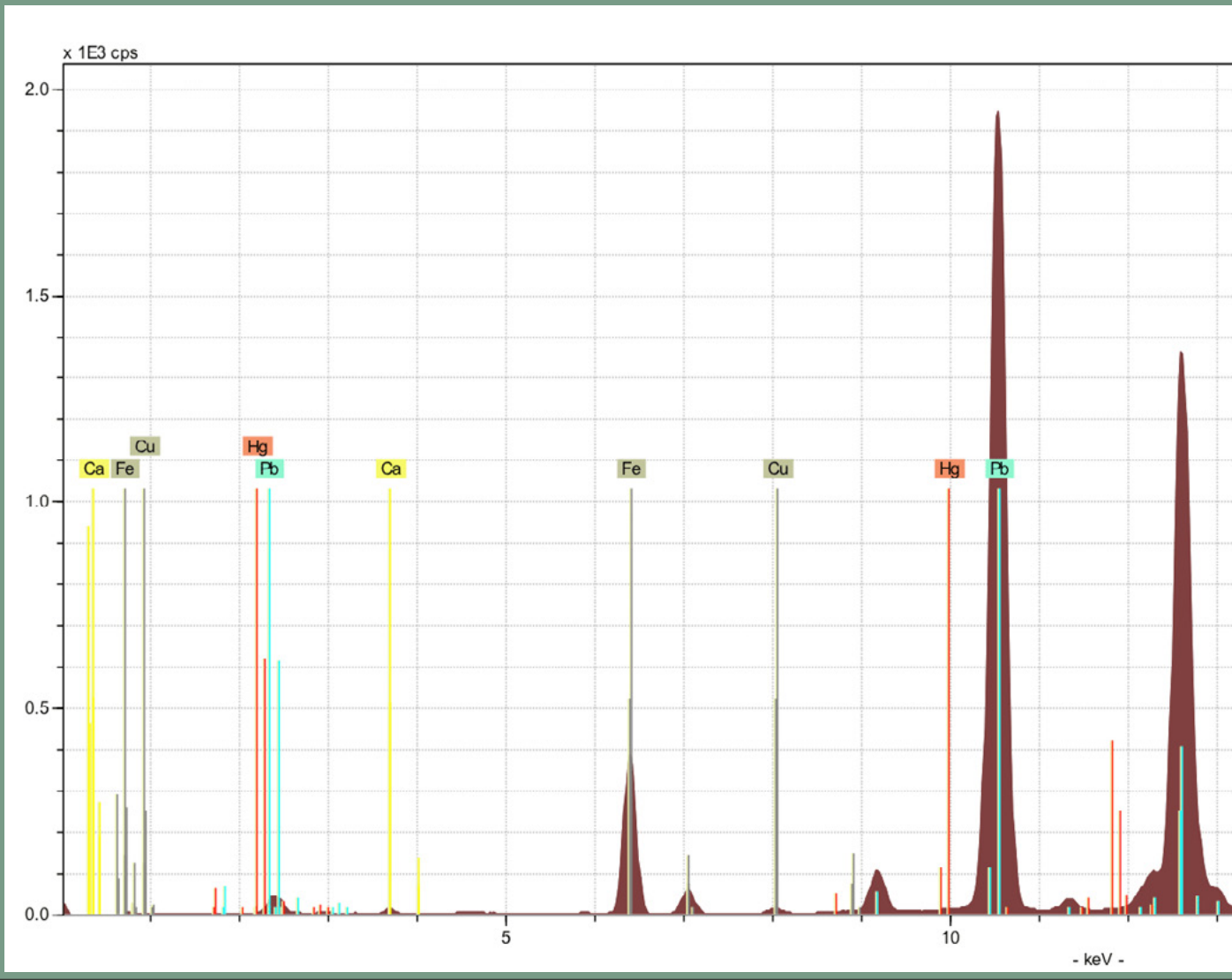
40 kV

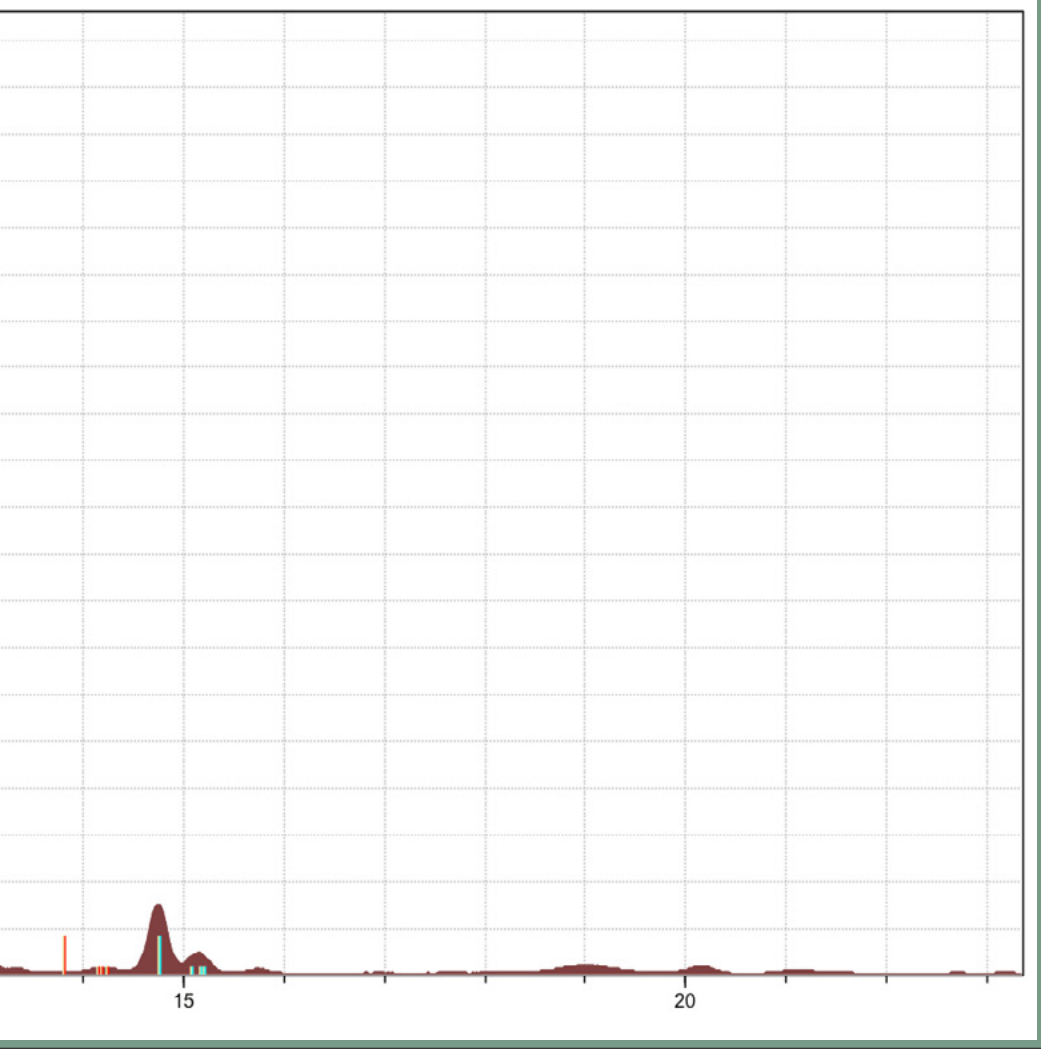
10 µA

air

filter: Ti 1 mil foil

time: 180 seconds




15
20

Location 8

Shadow area above location 6, the executioner on the ladder

Notes / possible pigments

Ochre pigments; lead white; chalk

Major intensity

Iron (Fe)

Lead (Pb)

Trace intensity

Calcium (Ca)

Copper (Cu)

Manganese (Mn)

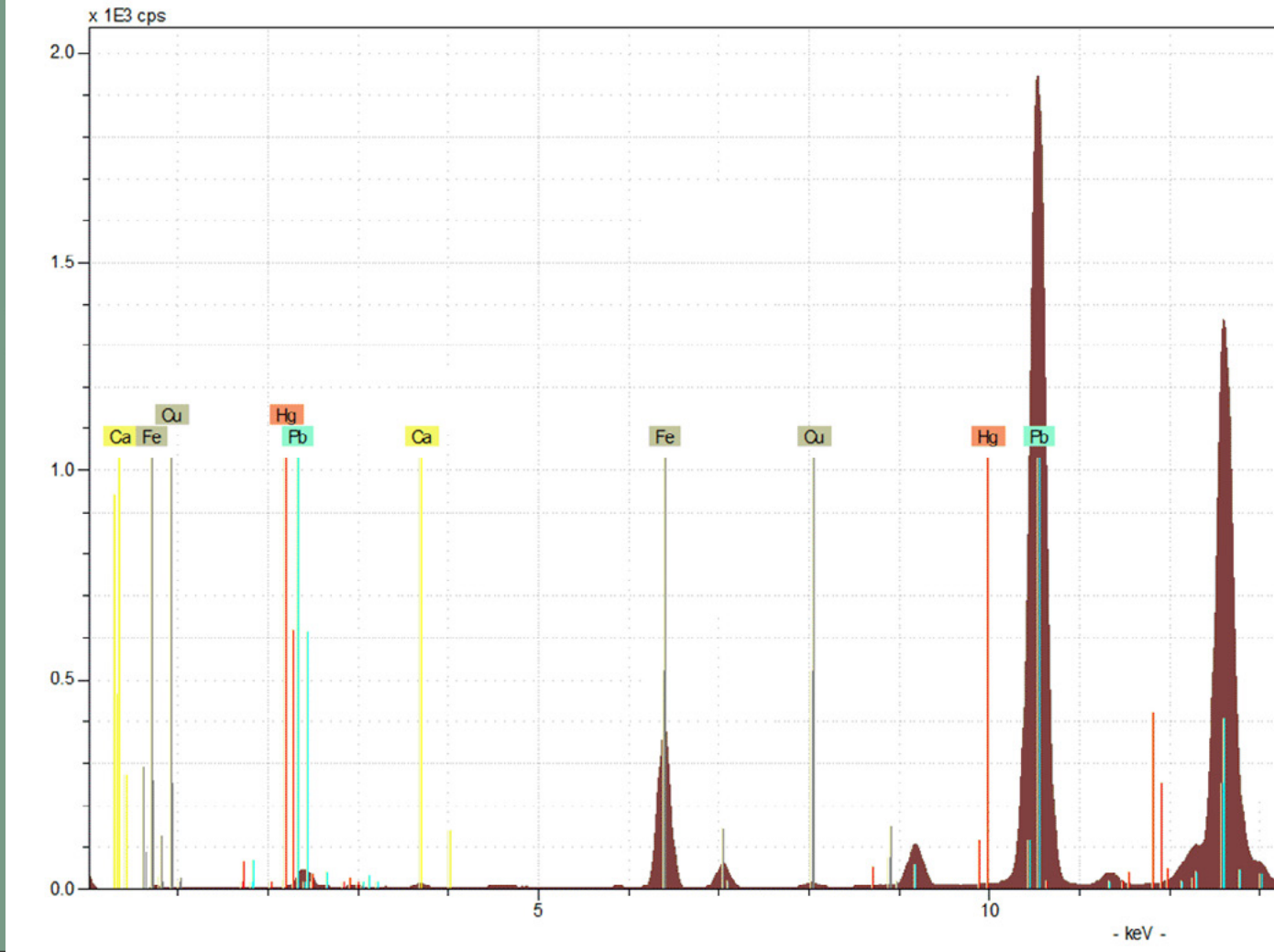
40 kV

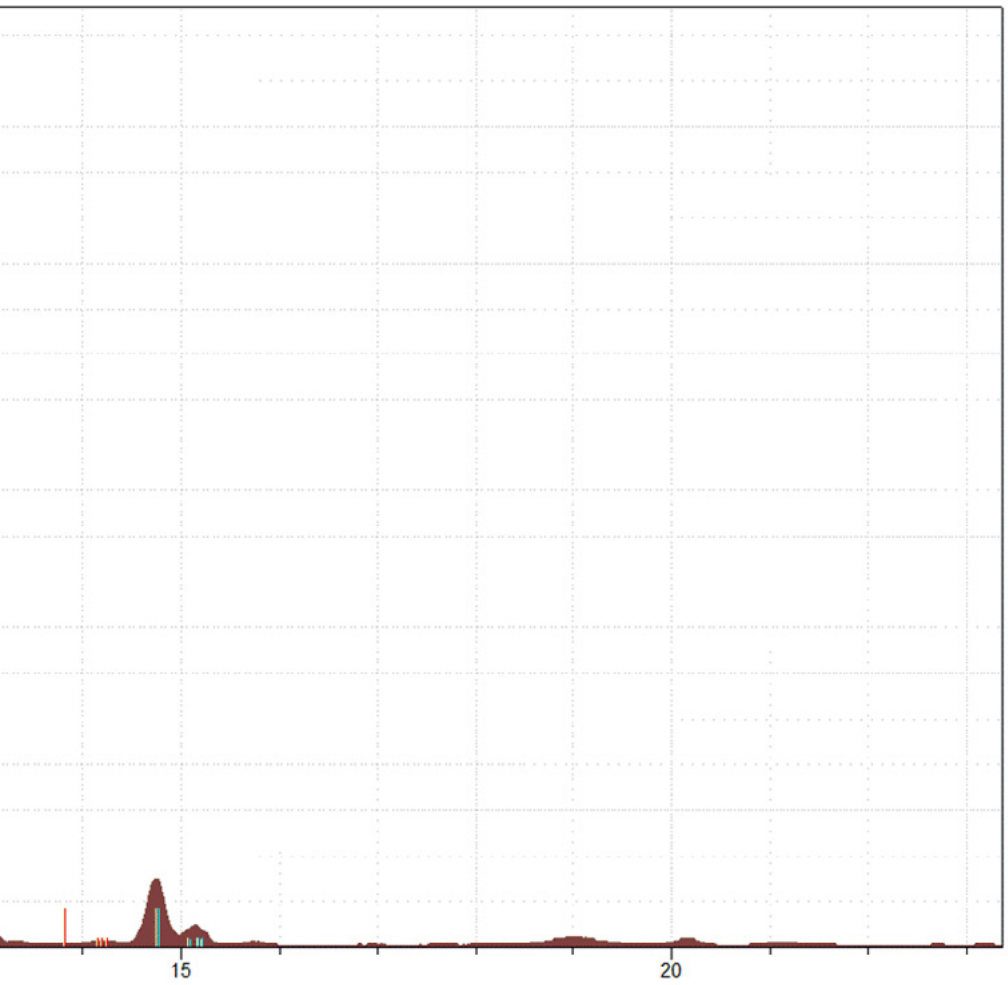
10 µA

air

filter: Ti 1 mil foil

time: 180 seconds




15
20

Location 9a

Highlight on yellow pants of the executioner on the ladder

Notes / possible pigments

Lead-tin yellow type II, confirmed by Raman spectroscopy; lead white; ochre pigments; chalk

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)
		Tin (Sn)
		Copper (Cu)

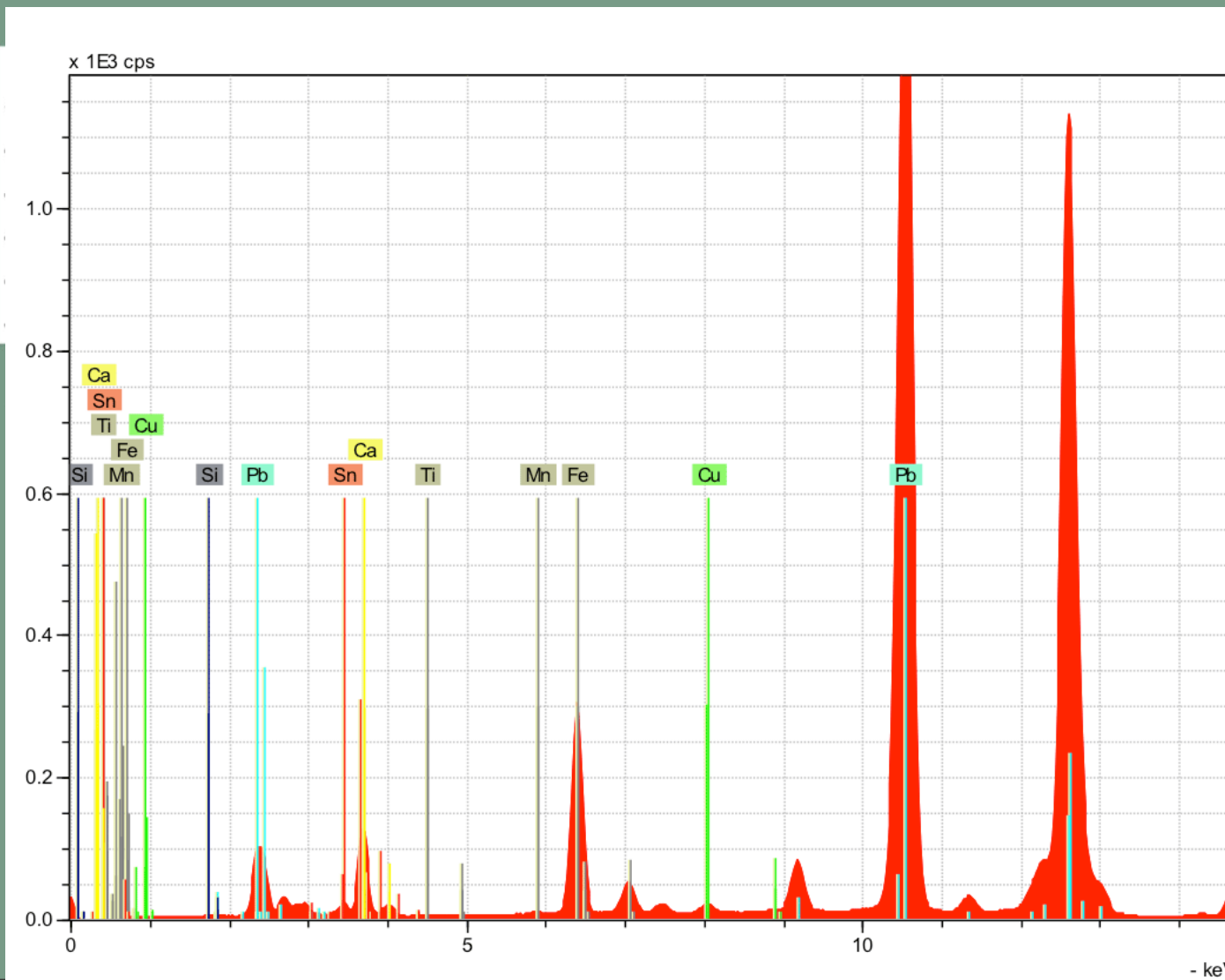
40 kV

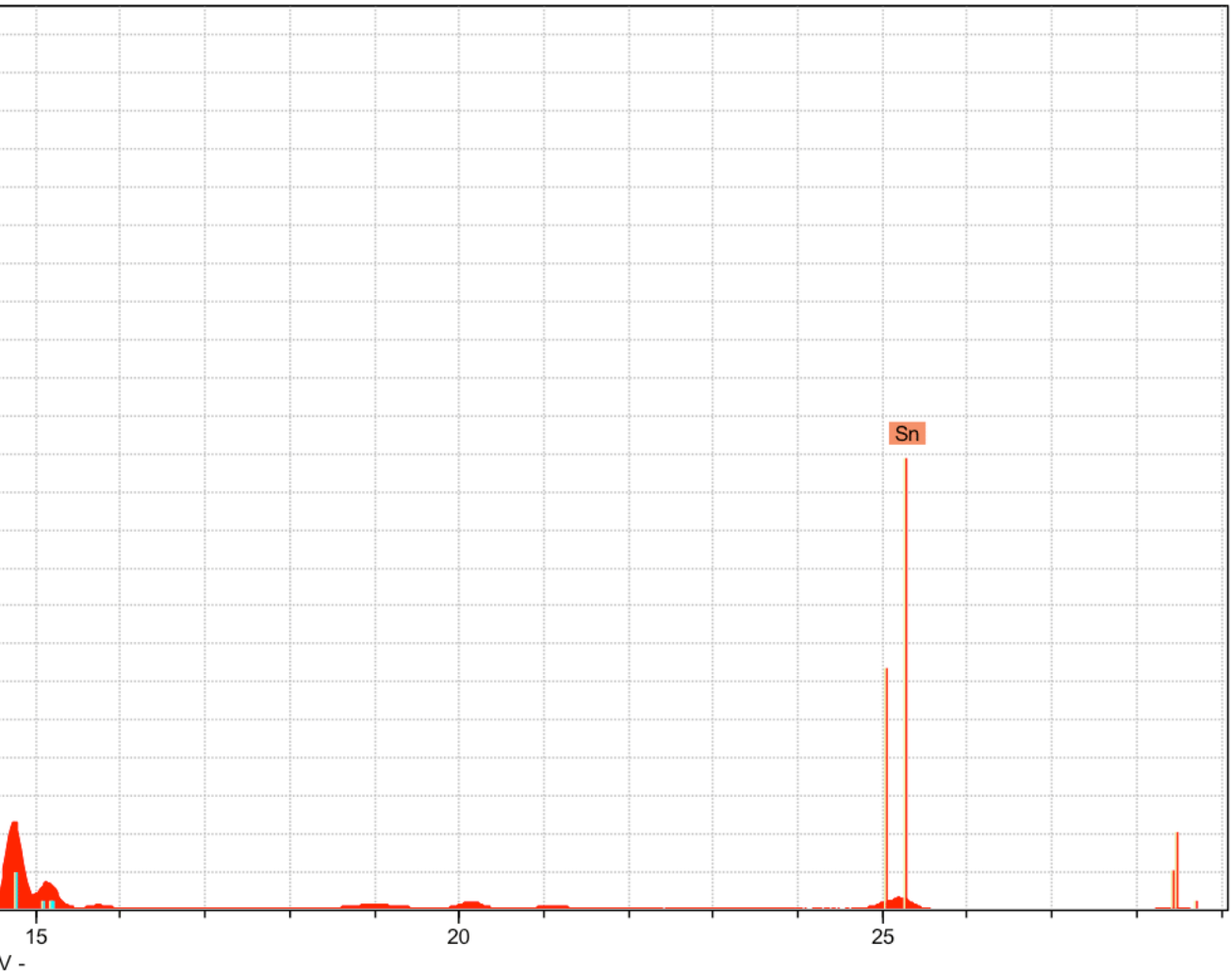
4.5 µA

air

filter: no

time: 120 seconds




Sn
15
20
25
V -

Location 9b

Highlight on yellow pants of the executioner on the ladder

Notes / possible pigments

Detail view of 9-A with only tin (Sn) peaks labeled. Lead-tin yellow type II, confirmed by Raman spectroscopy; lead white; ochre pigments; chalk

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)
		Tin (Sn)

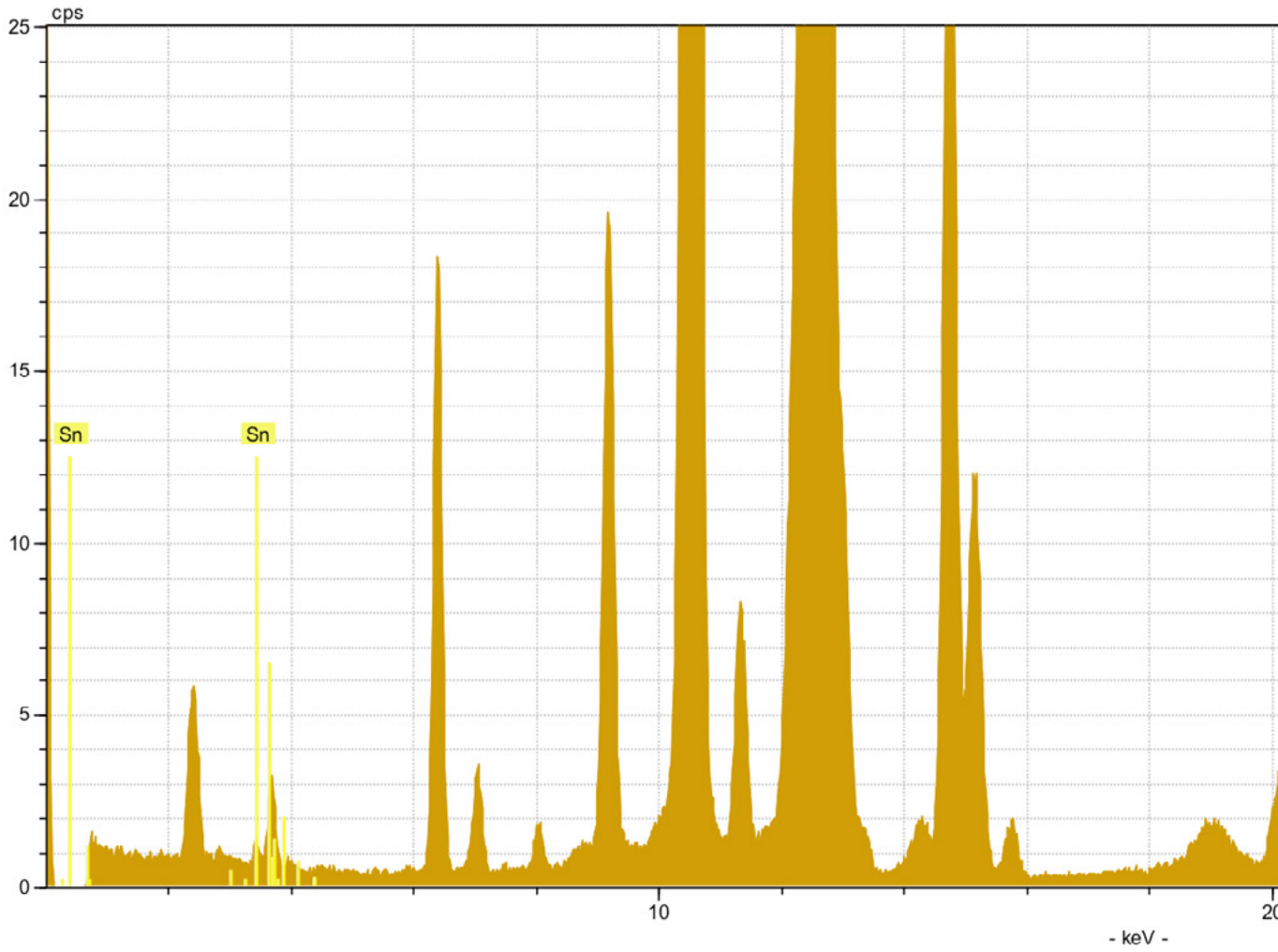
40 kV

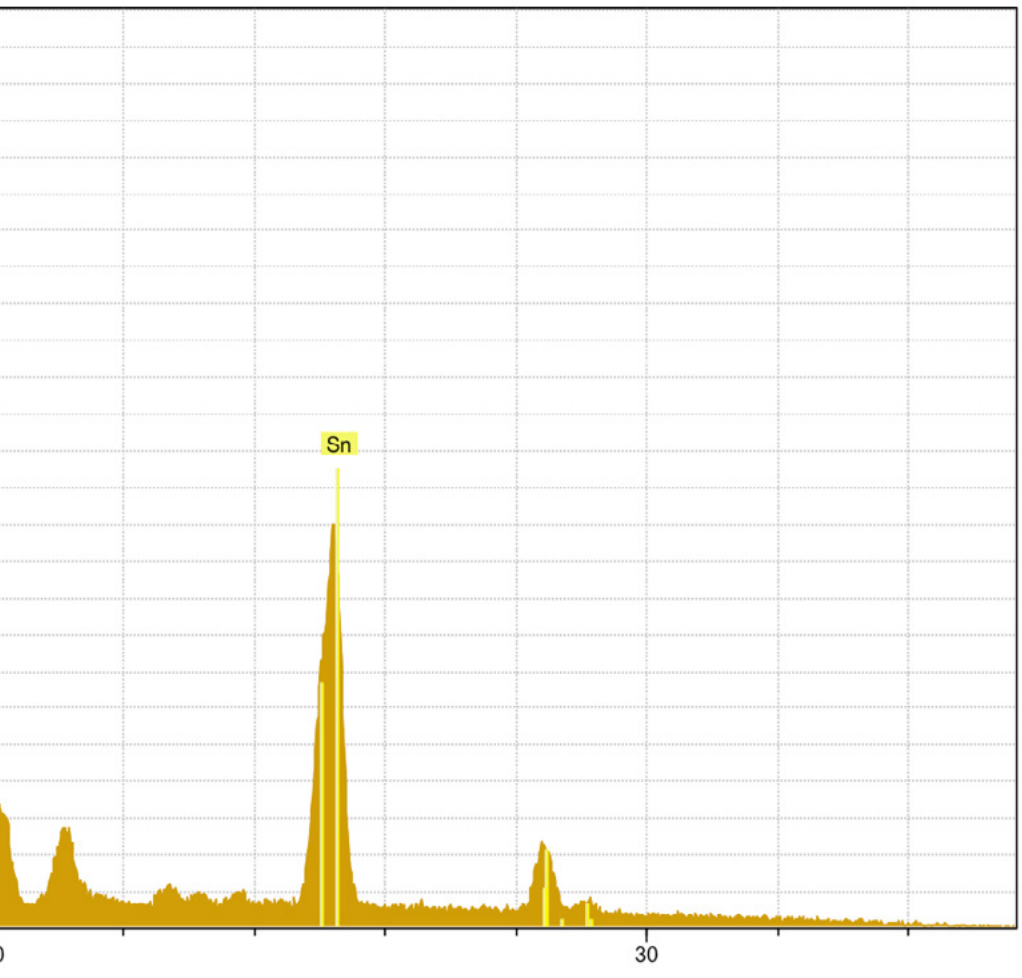
4.5 µA

air

filter: Cu 1 mil, Ti 1 mil, Al 12 mil foils

time: 120 seconds




Sn
30

Location 10

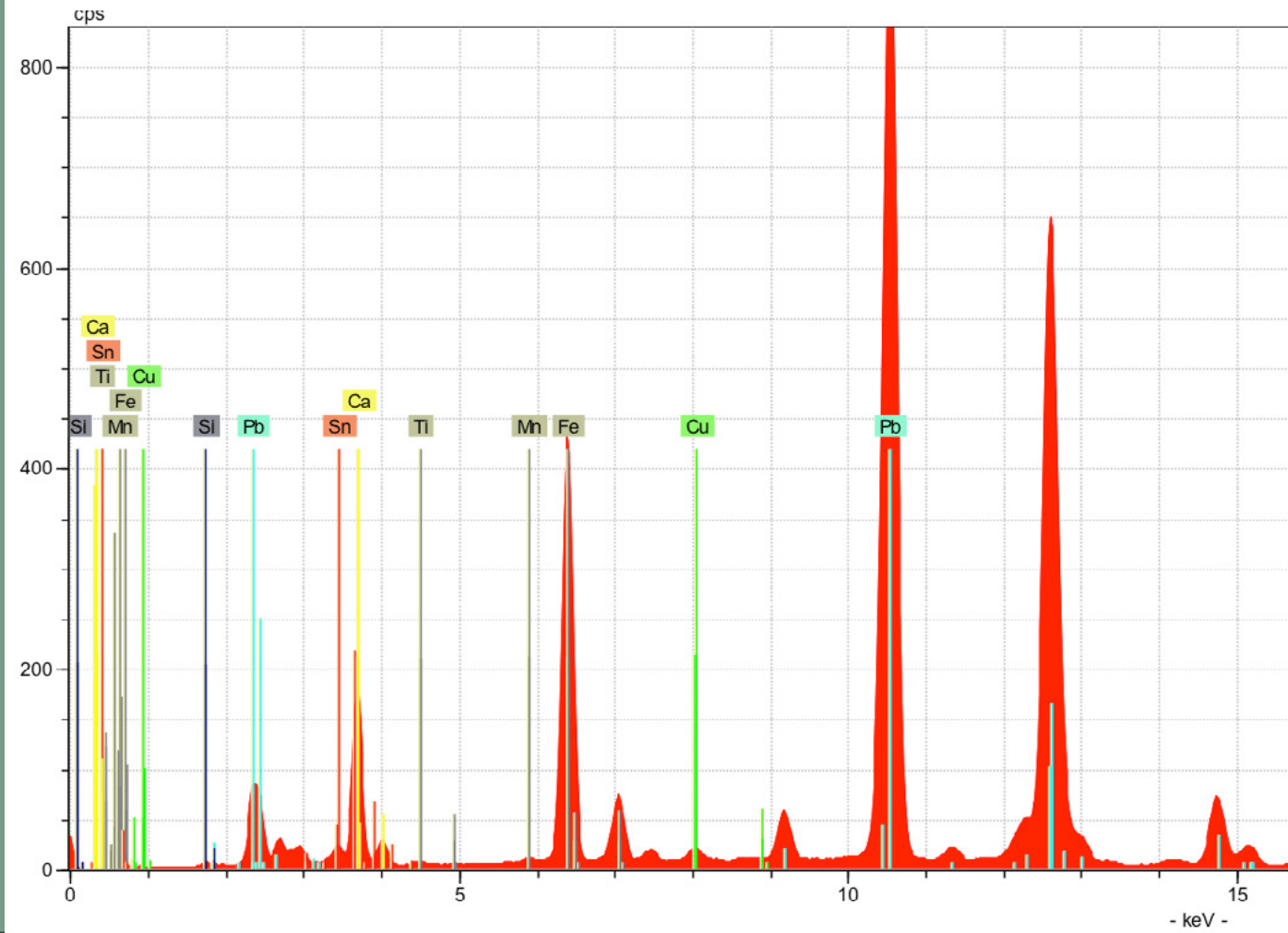
Executioner's yellow pants, the darker area to the left

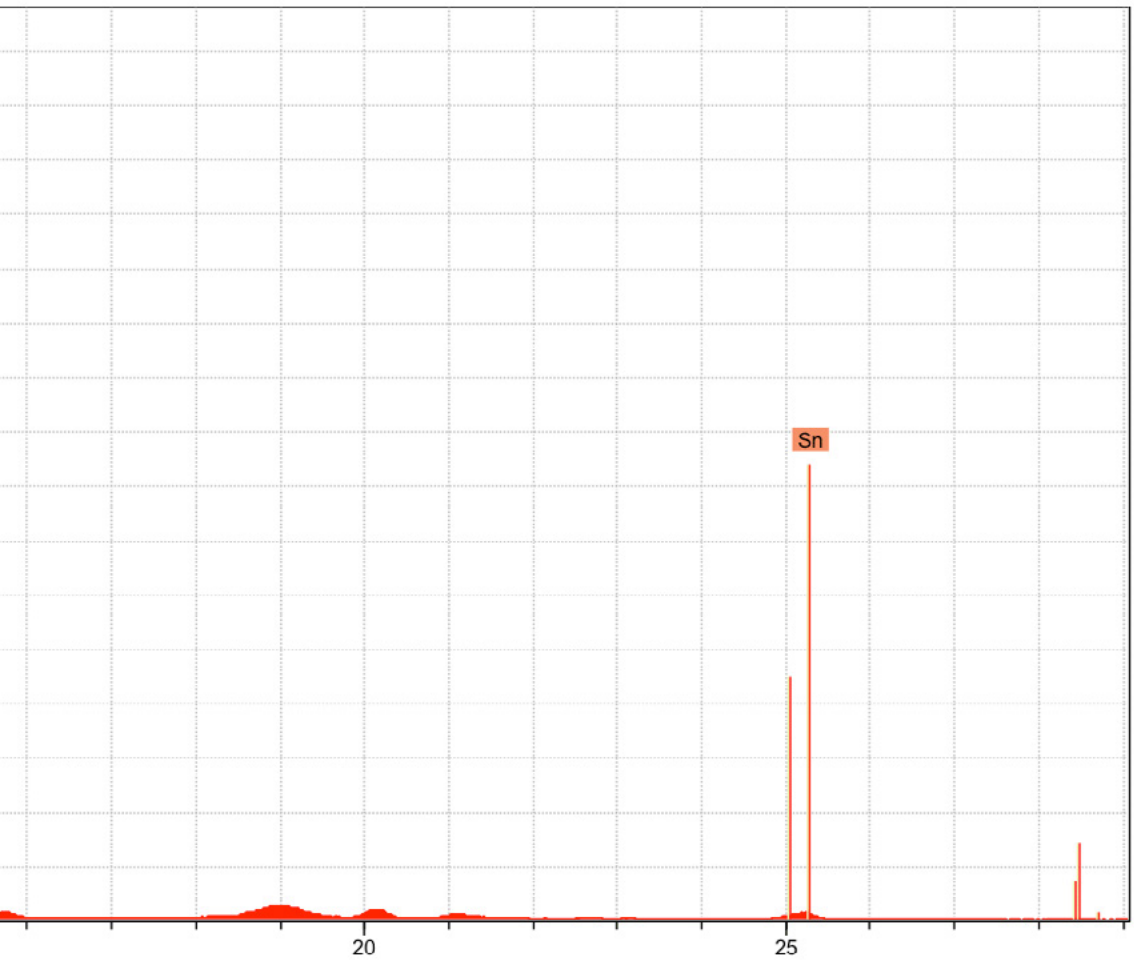
Notes / possible pigments

Lead-tin yellow type II, confirmed by Raman spectroscopy; lead white; ochre pigments (yellow ochre, confirmed by Raman spectroscopy); chalk

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Calcium (Ca)	Copper (Cu)
	Iron (Fe)	Manganese (Mn)
		Silicon (Si)
		Tin (Sn)
		Titanium (Ti)

40 kV
4.5 µA
air
filter: no
time: 120 seconds




Sn
20
25

Location 11

Highlight of the scapula of the executioner on the ladder

Notes / possible pigments

Lead white; ochre pigments; chalk

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)
		Copper (Cu)

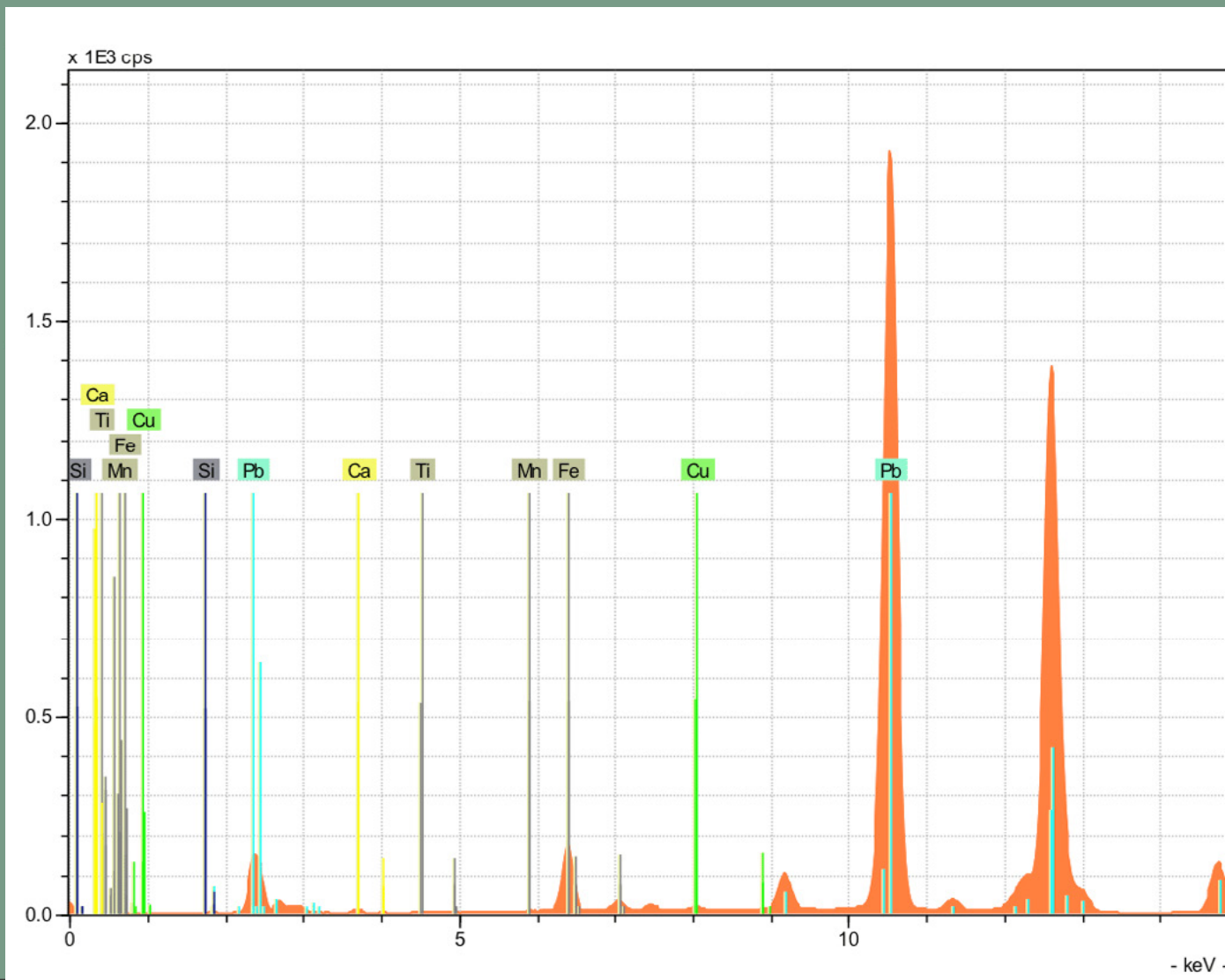
40 kV

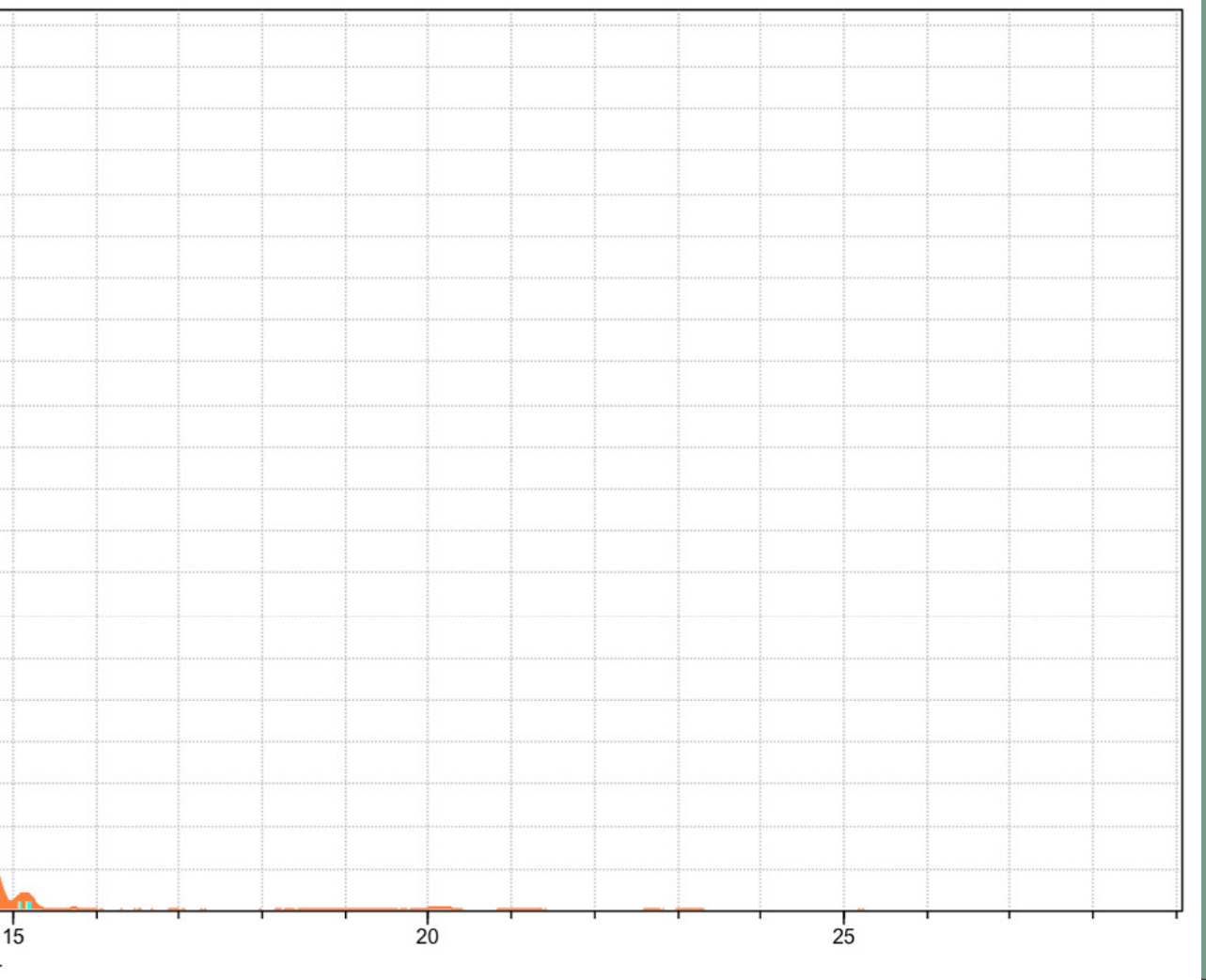
4.5 µA

air

filter: no

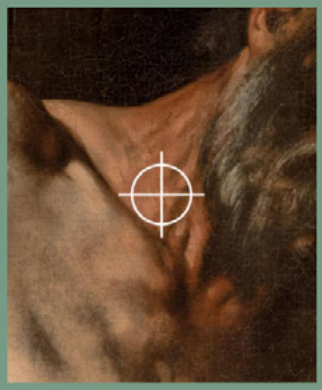
time: 120 seconds




15
20
25

Location 12

Saint Andrew's neck



Notes / possible pigments

Lead white; ochre pigments; chalk

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)
		Copper (Cu)

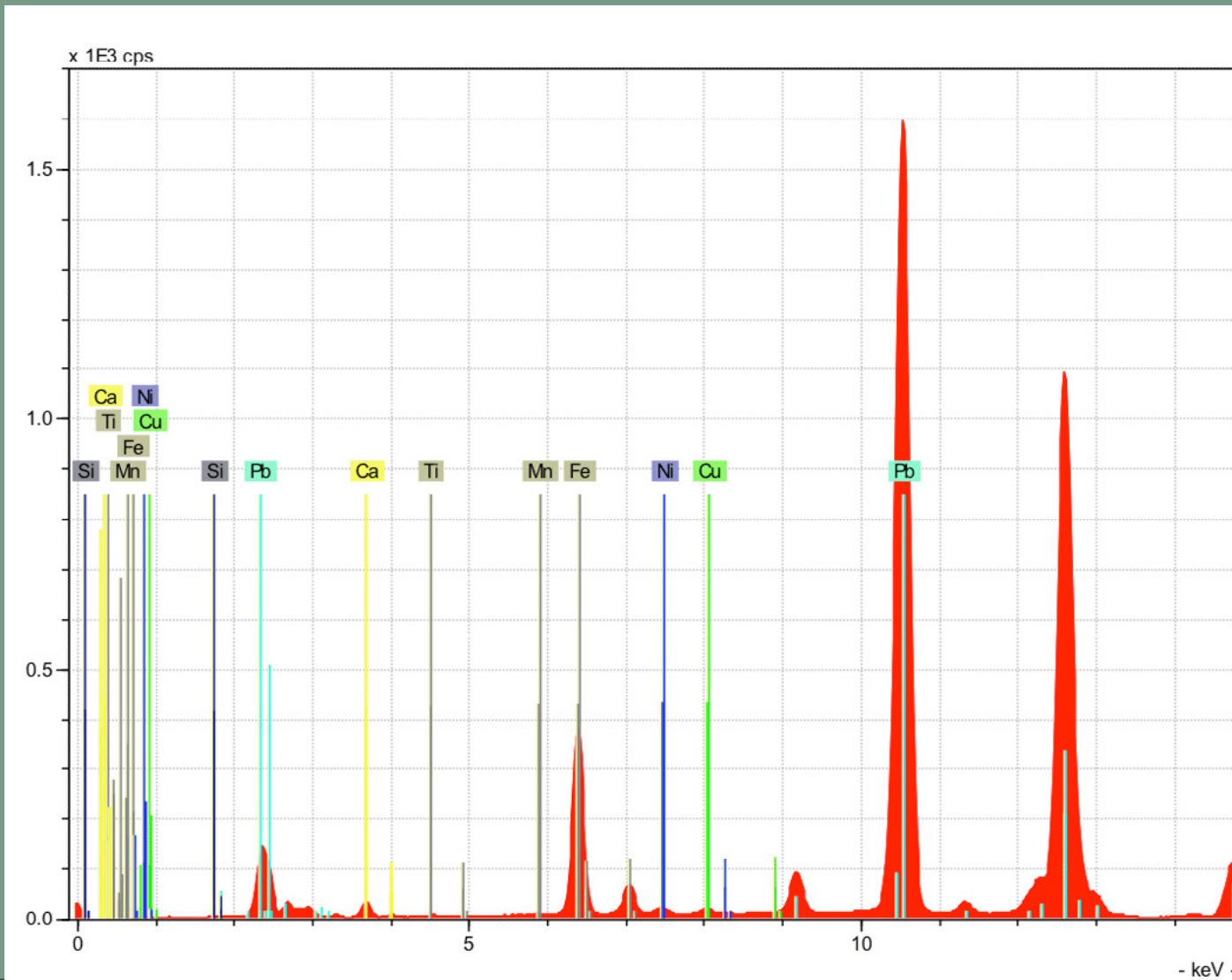
40 kV

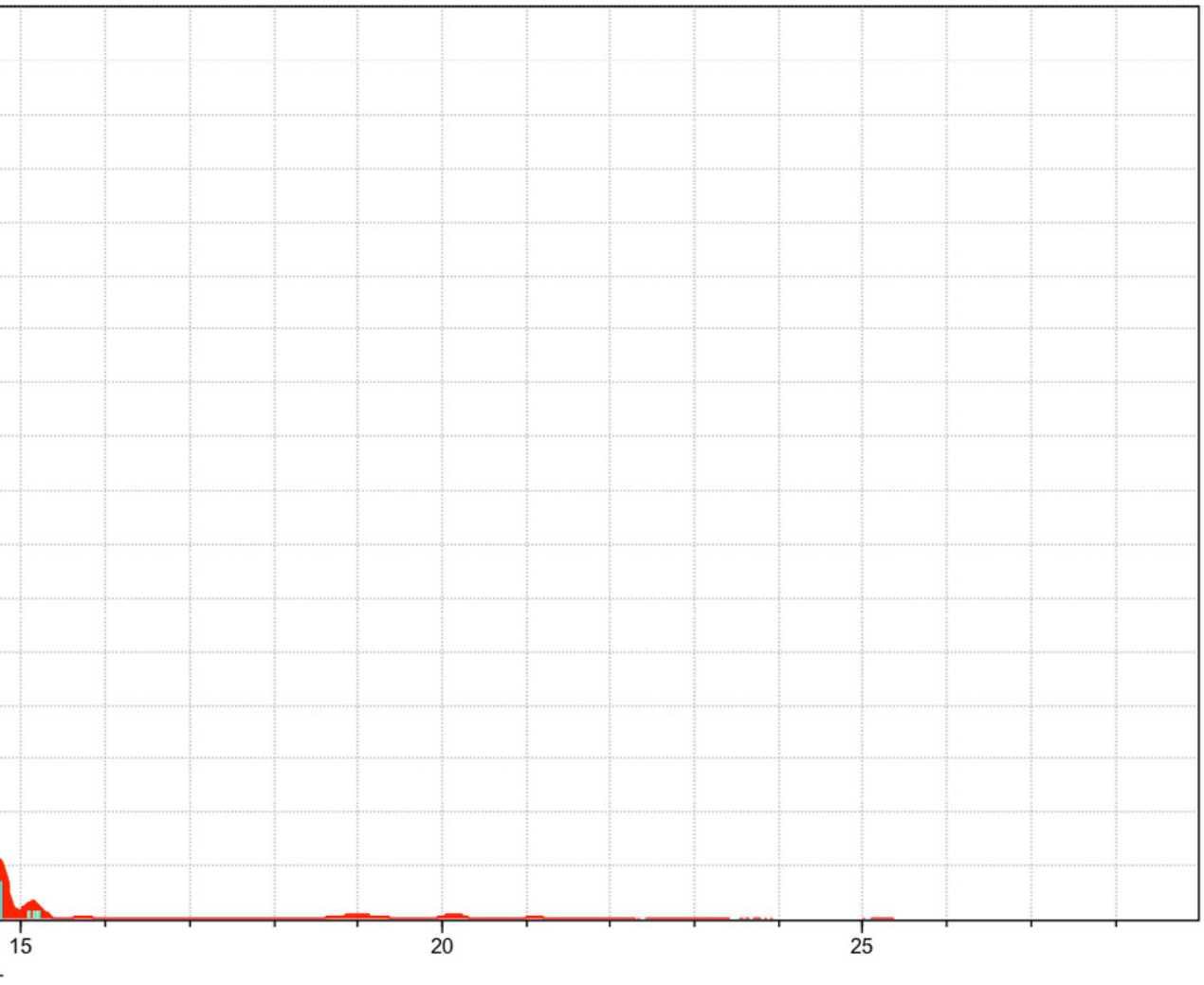
4.5 µA

air

filter: no

time: 120 seconds




15
20
25

Location 13

Highlight in Saint Andrew's red garment

Notes / possible pigments

Vermilion; lead white; umber; copper-based pigment

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Calcium (Ca)	Copper (Cu)
	Iron (Fe)	Manganese (Mn)
	Mercury (Hg)	

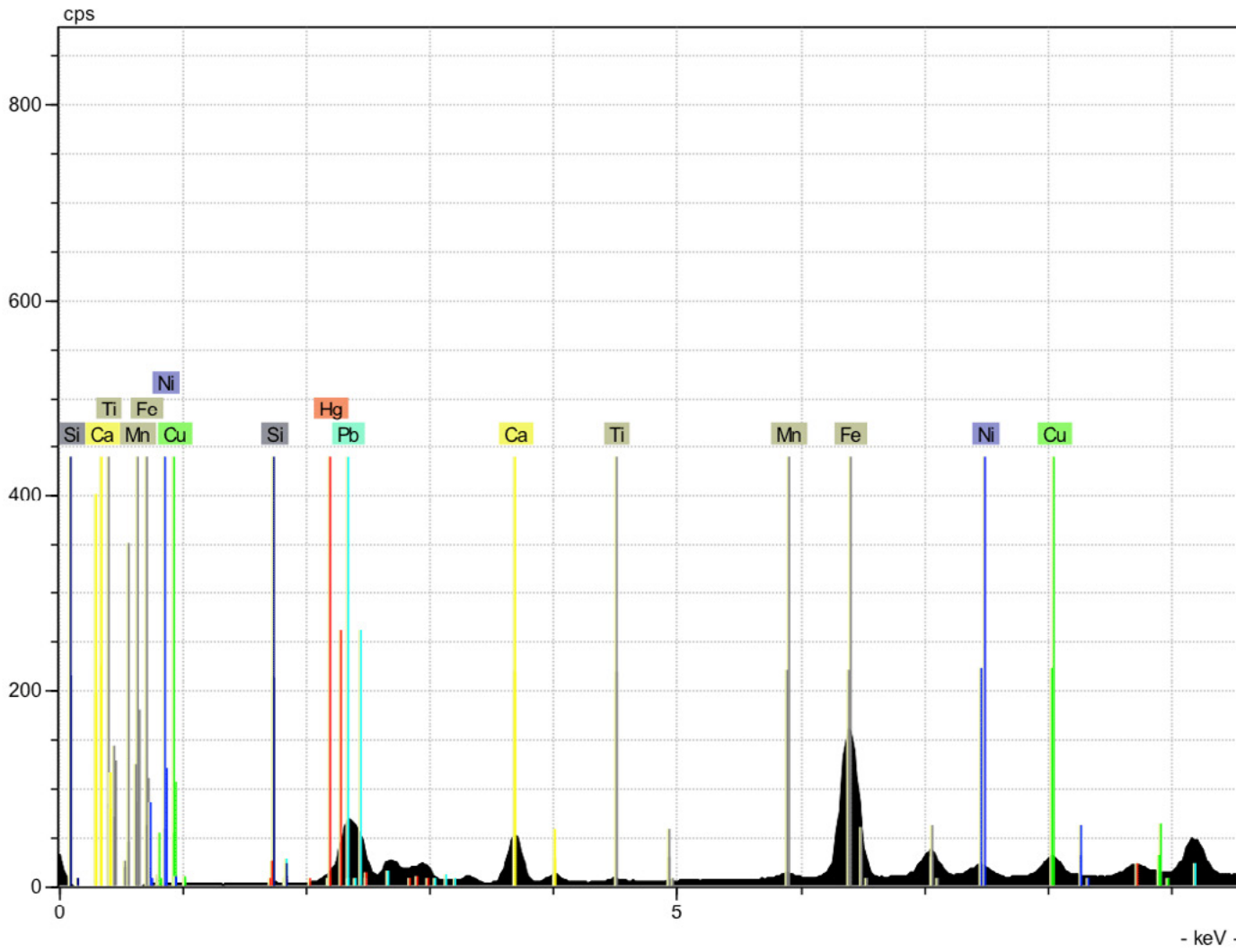
40 kV

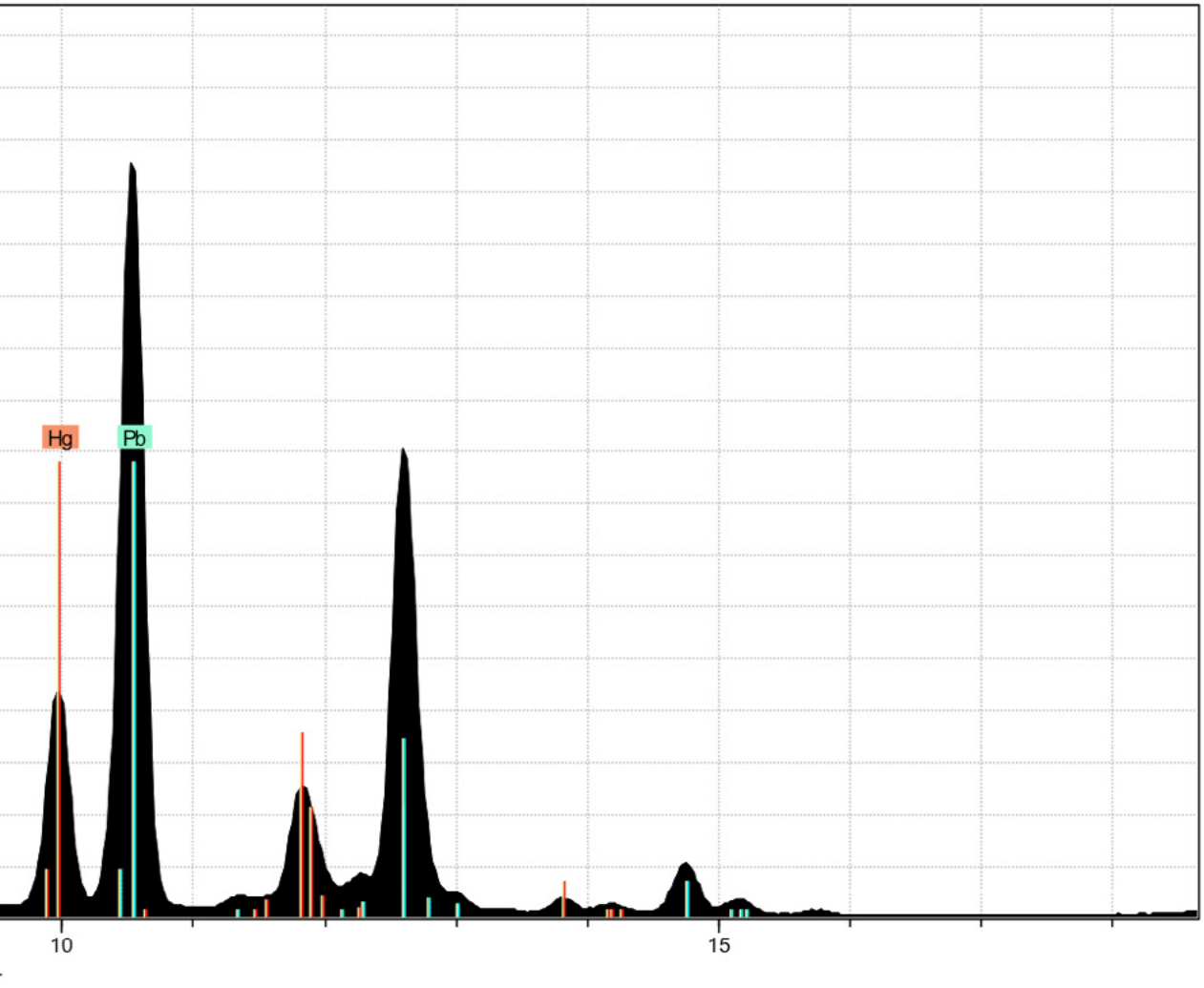
4.5 µA

air

filter: no

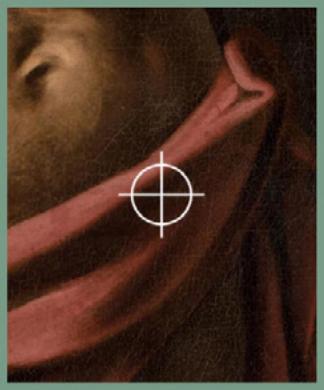
time: 120 seconds




Hg
Pb
10
15

Location 14

Shadow in Saint Andrew's red garment



Notes / possible pigments

Lead white; iron-based pigment; vermilion; umber; copper-based pigment; chalk

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Copper (Cu)
Lead (Pb)	Mercury (Hg)	Manganese (Mn)
		Potassium (K)

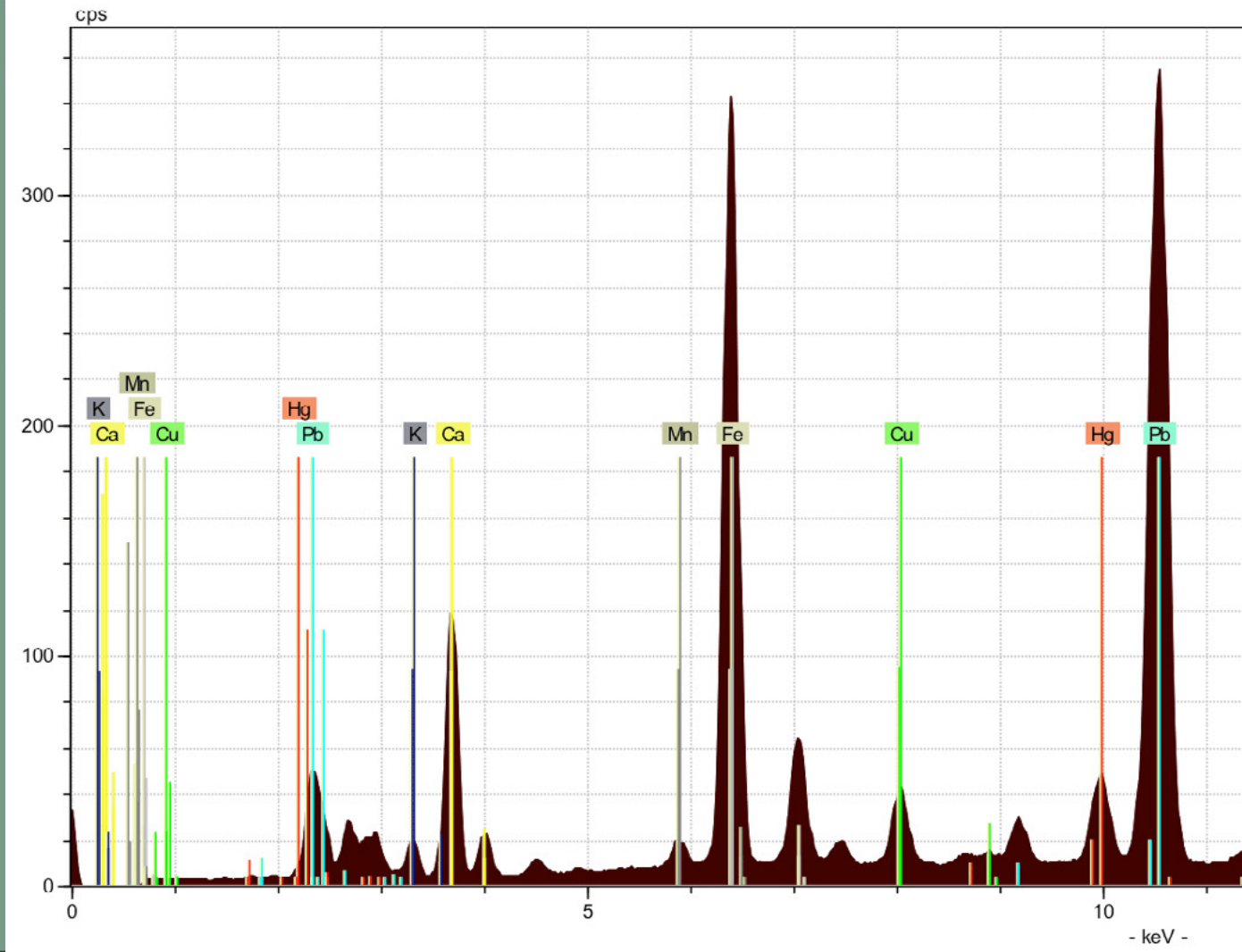
40 kV

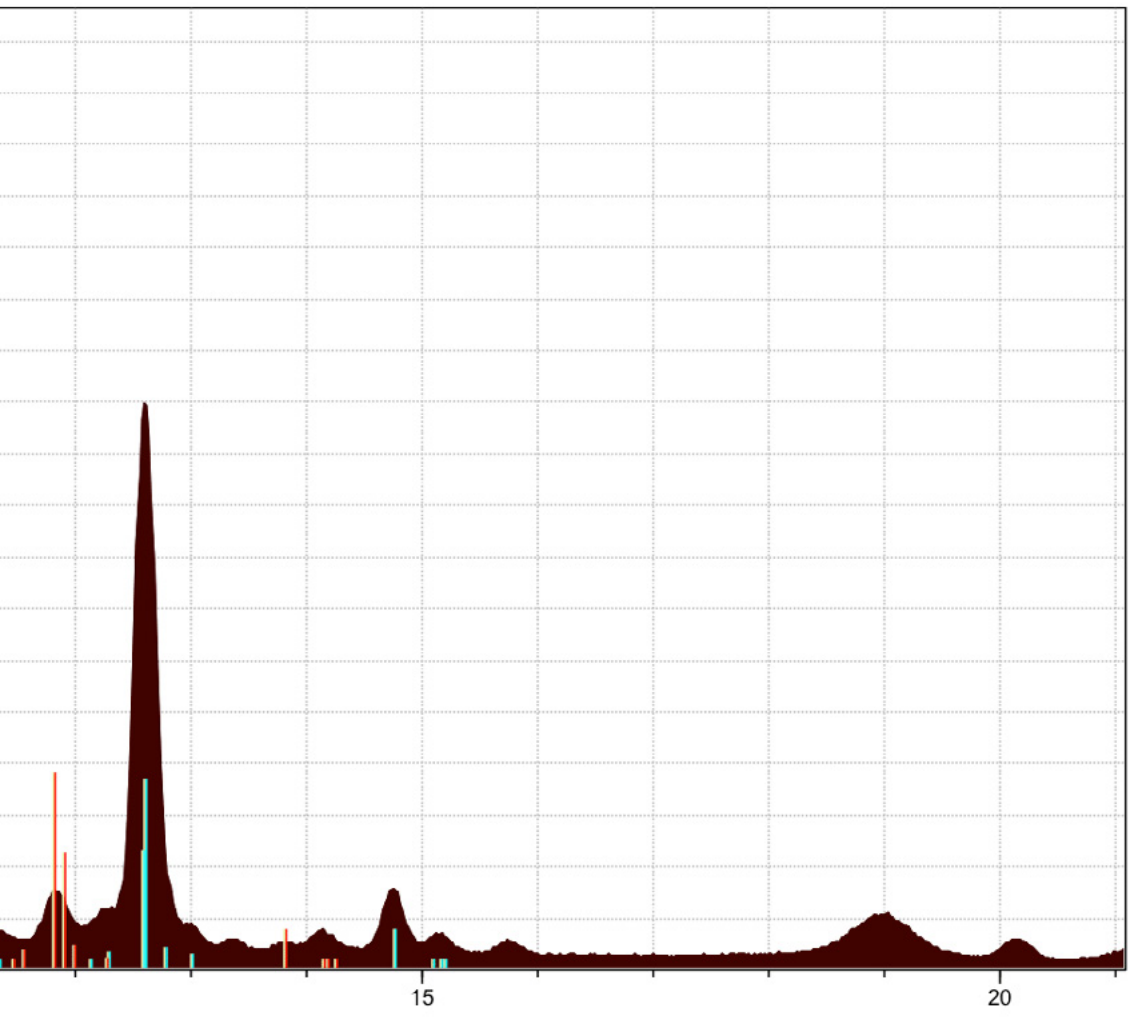
4.5 µA

air

filter: no

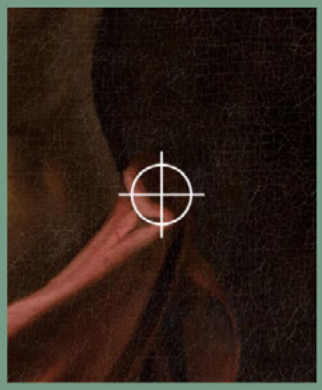
time: 120 seconds




15
20

Location 15

Shadow in Saint Andrew's red garment



Notes / possible pigments

Lead white; iron-based pigment; copper-based pigment; vermilion

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Manganese (Mn)
Lead (Pb)	Copper (Cu)	Mercury (Hg)
		Potassium (K)

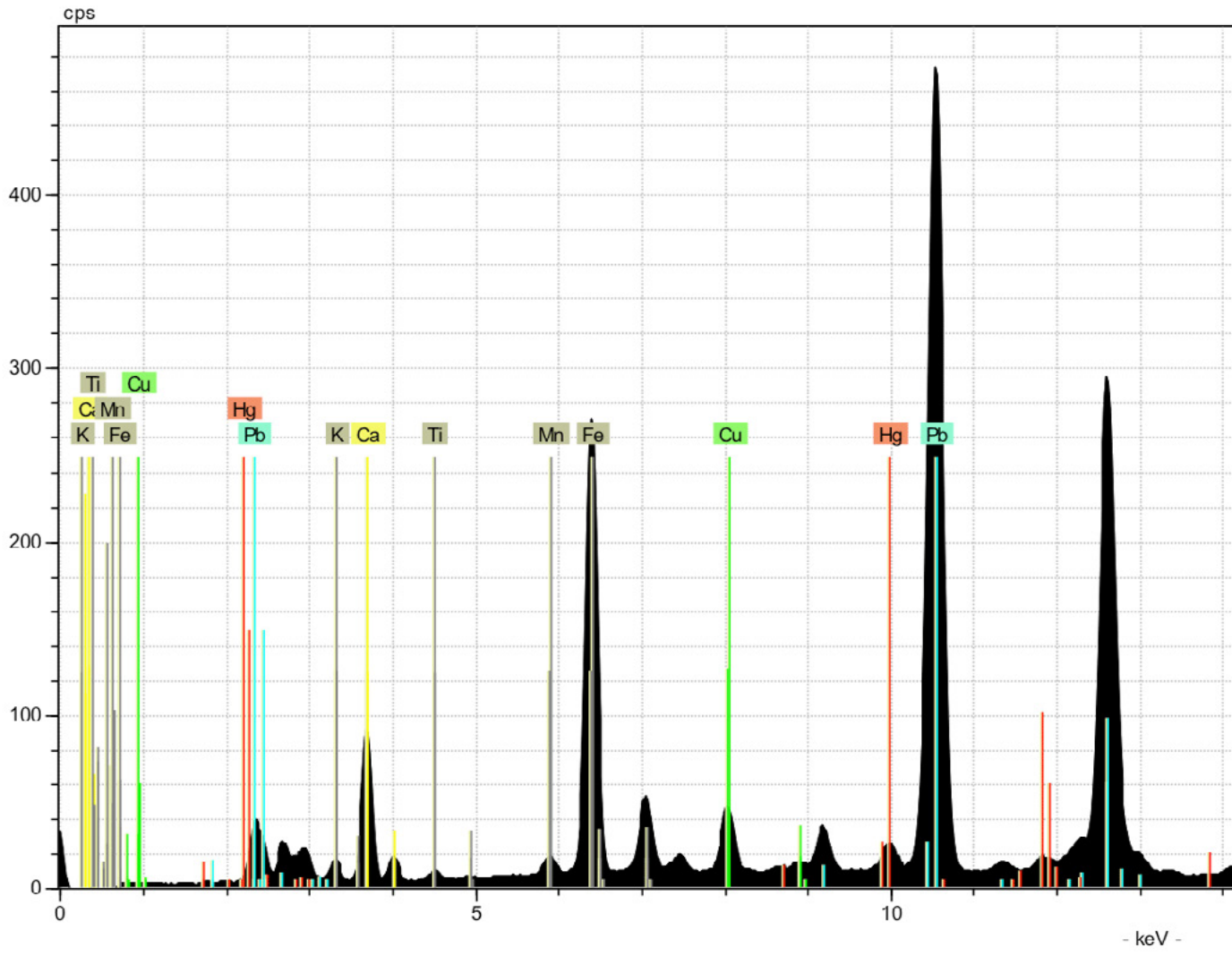
40 kV

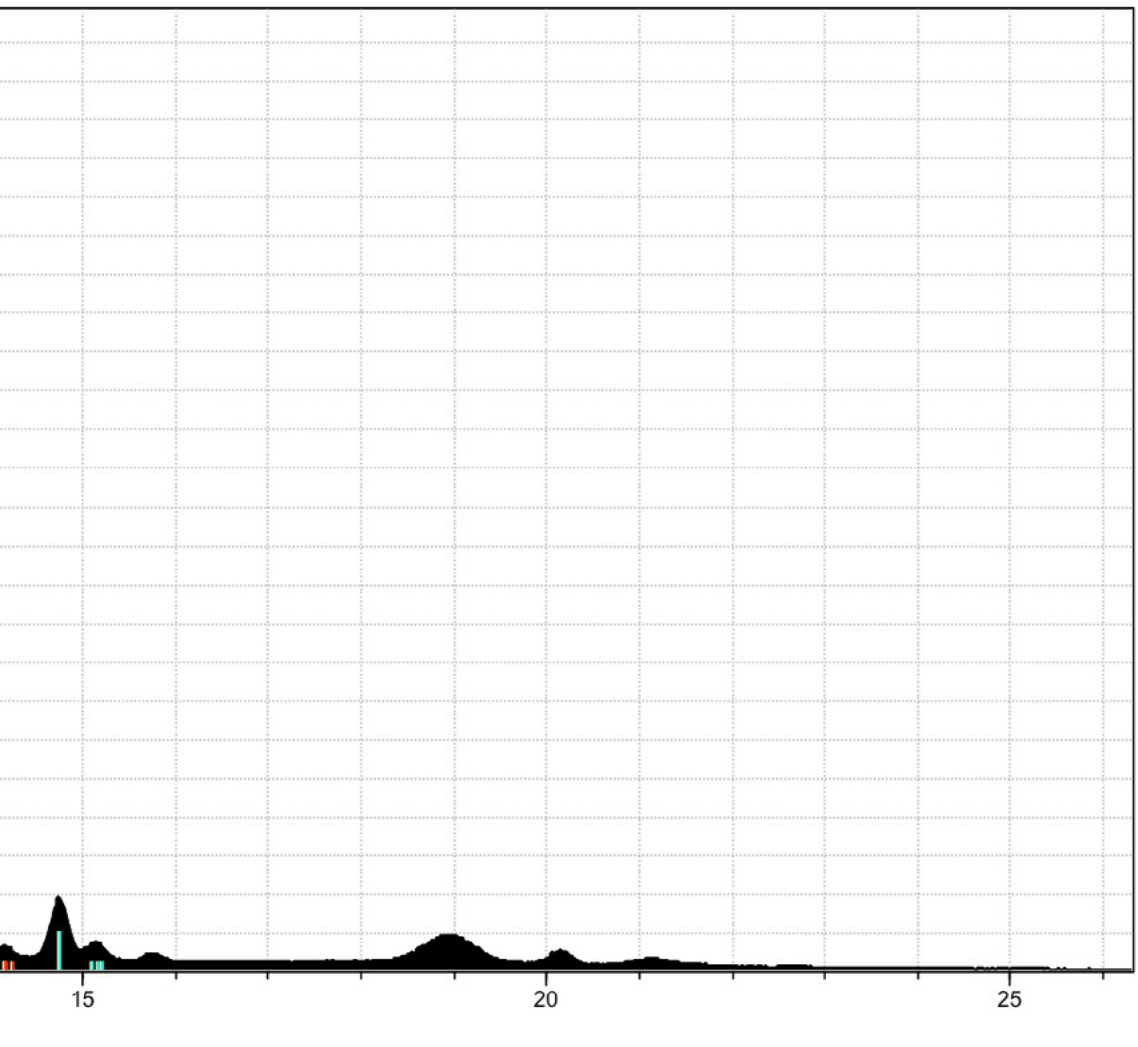
4.5 µA

air

filter: no

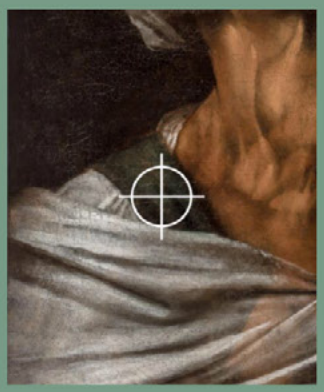
time: 120 seconds




15
20
25

Location 16

The old woman's green shoulder strap



Notes / possible pigments

Dark blue-green area with strong copper intensity: azurite, confirmed by Raman spectroscopy; lead white; chalk

Major intensity	Minor intensity
Copper (Cu)	Calcium (Ca)
Lead (Pb)	Iron (Fe)

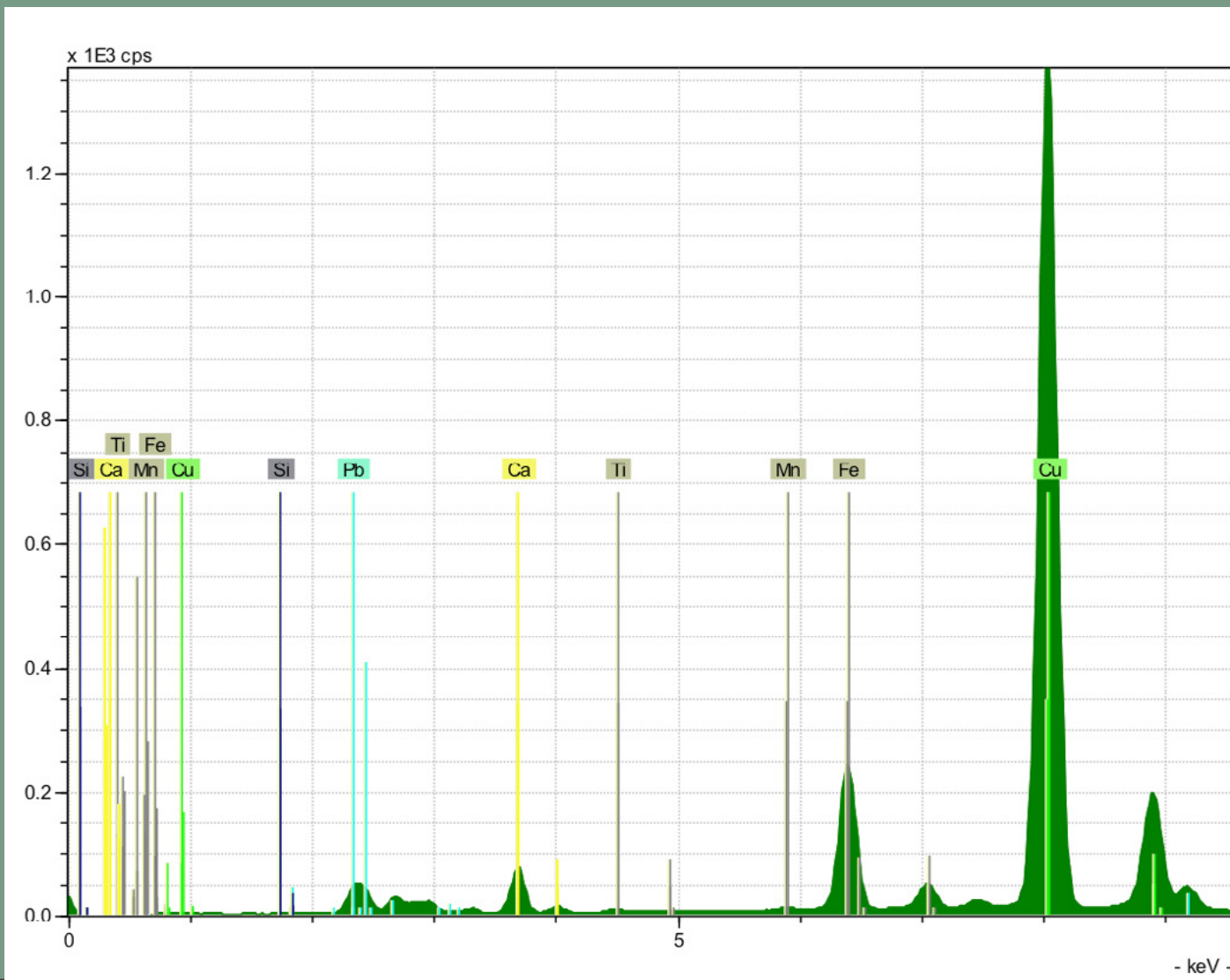
40 kV

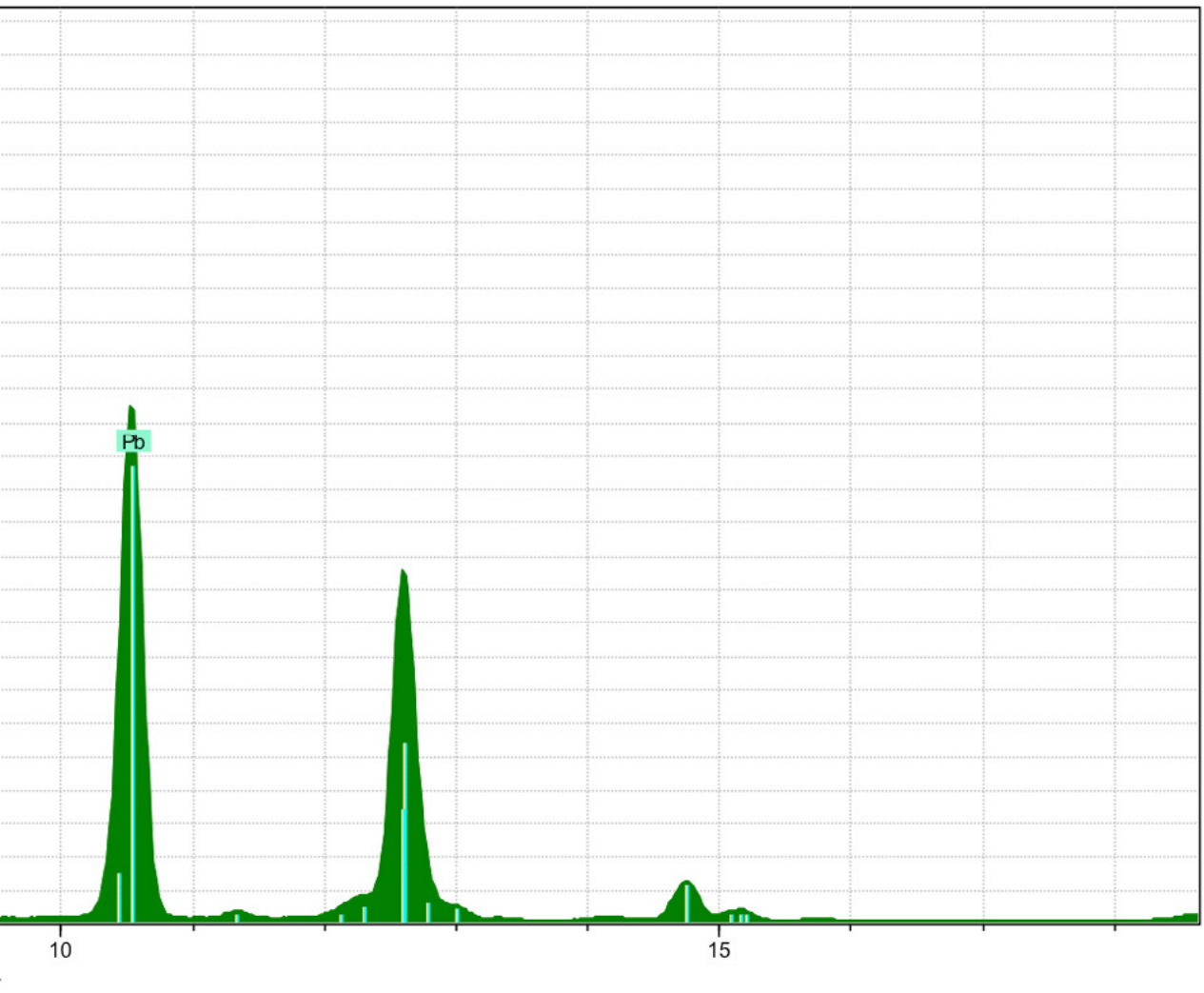
4.5 µA

air

filter: no

time: 120 seconds




Pb
10
15

Location 17

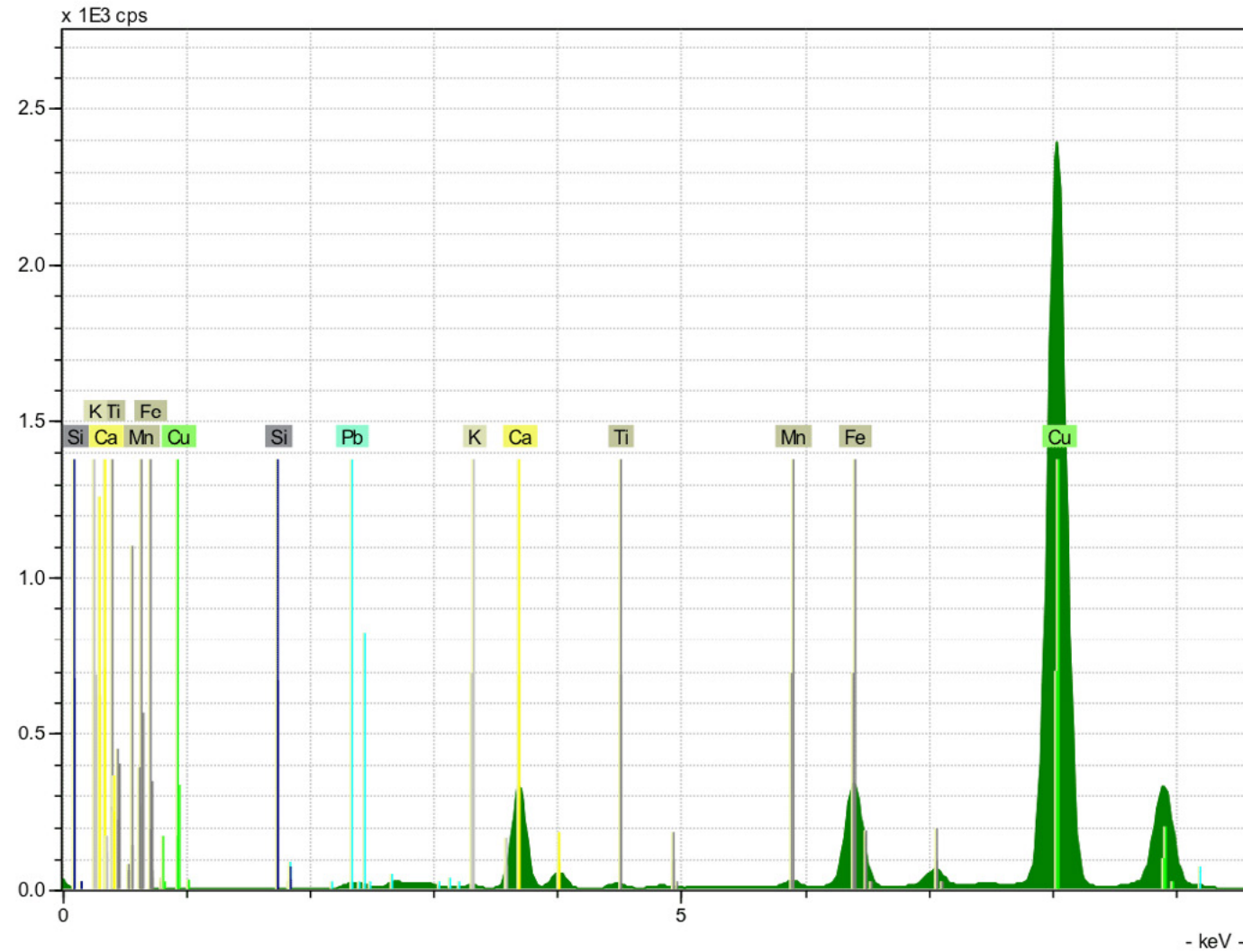
The soldier's green waistcoat

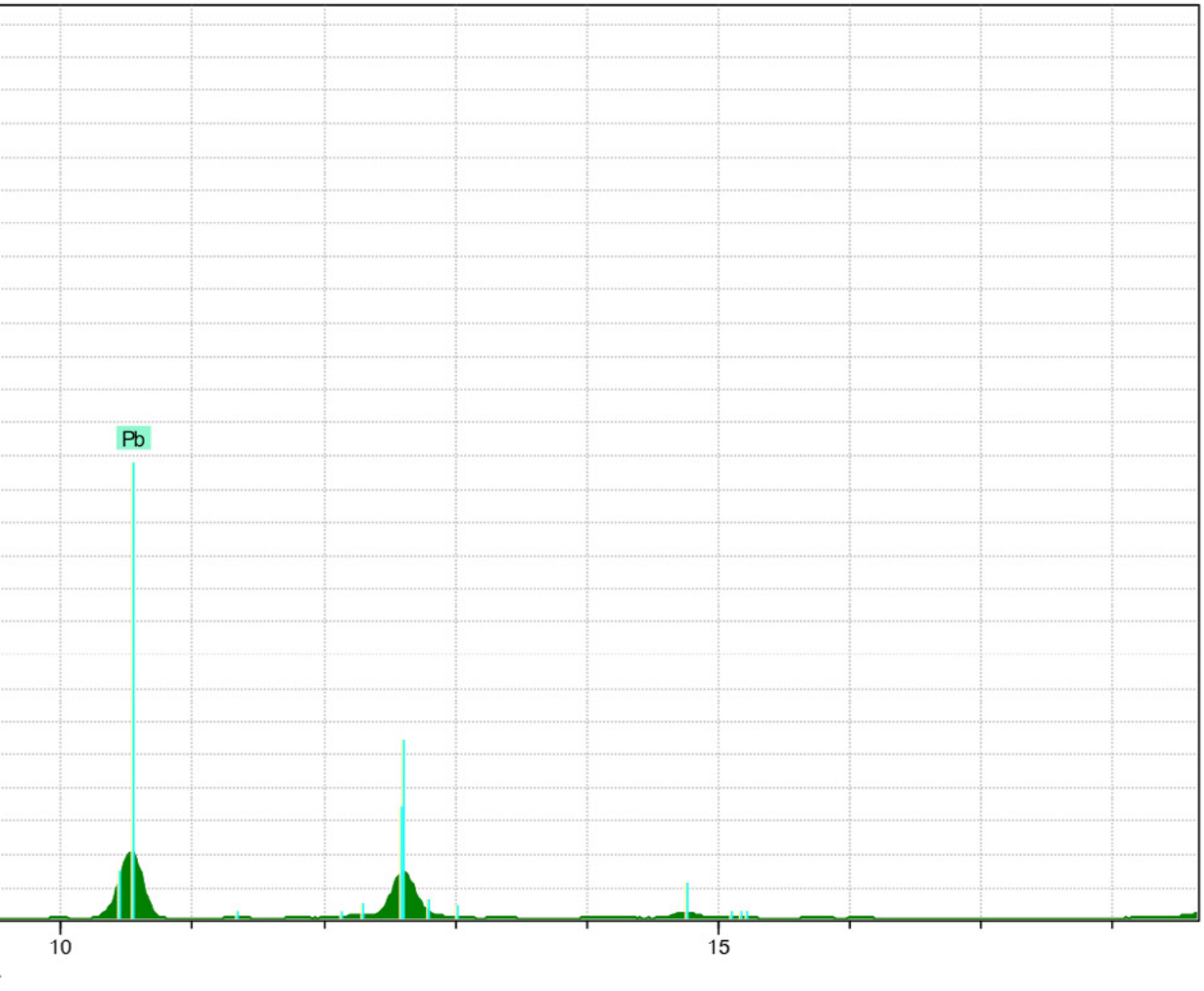
Notes / possible pigments

Malachite, identified by Raman spectroscopy;
lead white; umber

Major intensity	Minor intensity	Trace intensity
Copper (Cu)	Calcium (Ca)	Manganese (Mn)
	Iron (Fe)	Potassium (K)
	Lead (Pb)	

40 kV
4.5 µA
air
filter: no
time: 120 seconds




Pb
10
15

Location 18

The soldier's green waistcoat

Notes / possible pigments

Malachite, identified by Raman spectroscopy; lead white; umber

Major intensity	Minor intensity	Trace intensity
Copper (Cu)	Calcium (Ca)	Lead (Pb)
	Iron (Fe)	Manganese (Mn)
		Potassium (K)

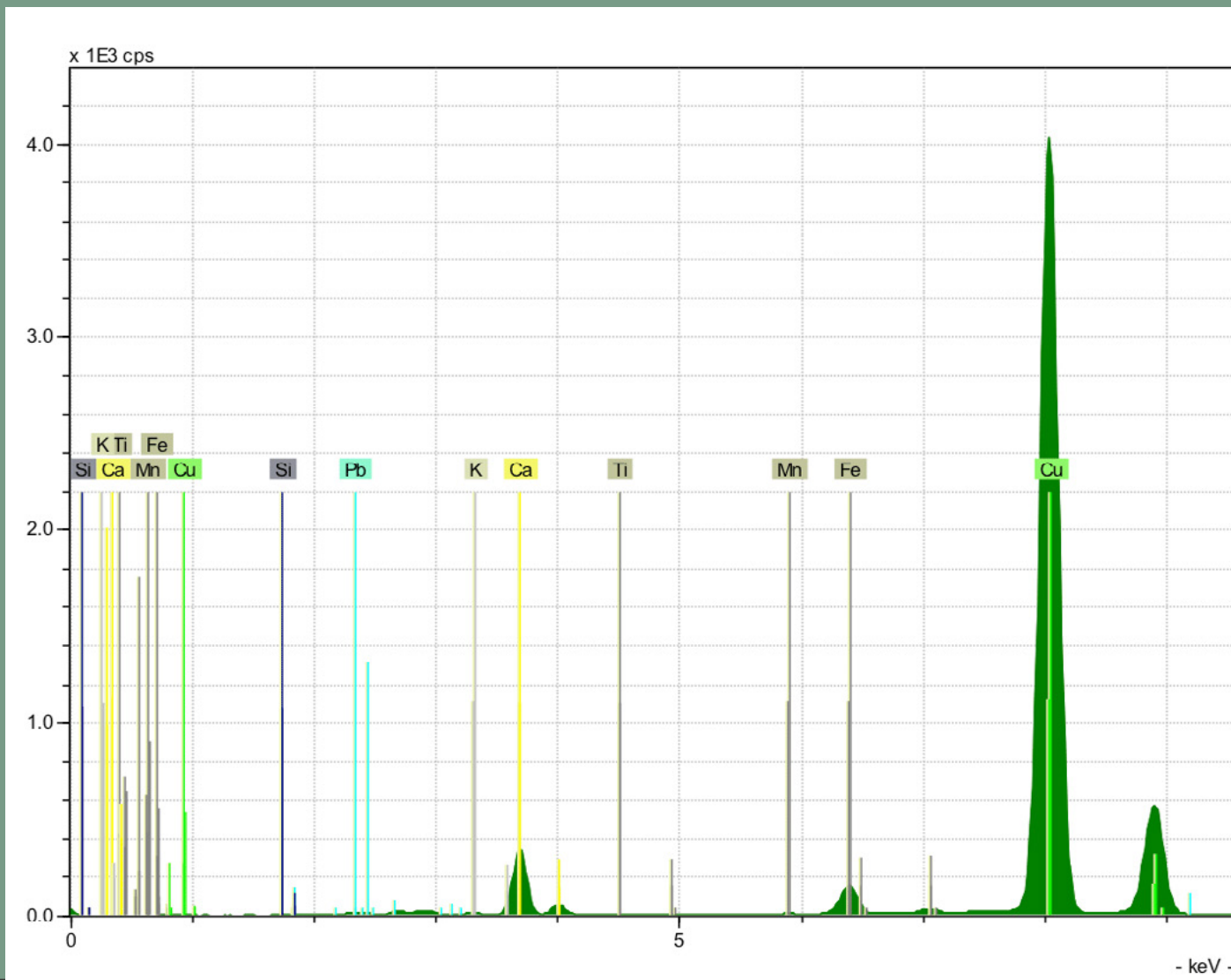
40 kV

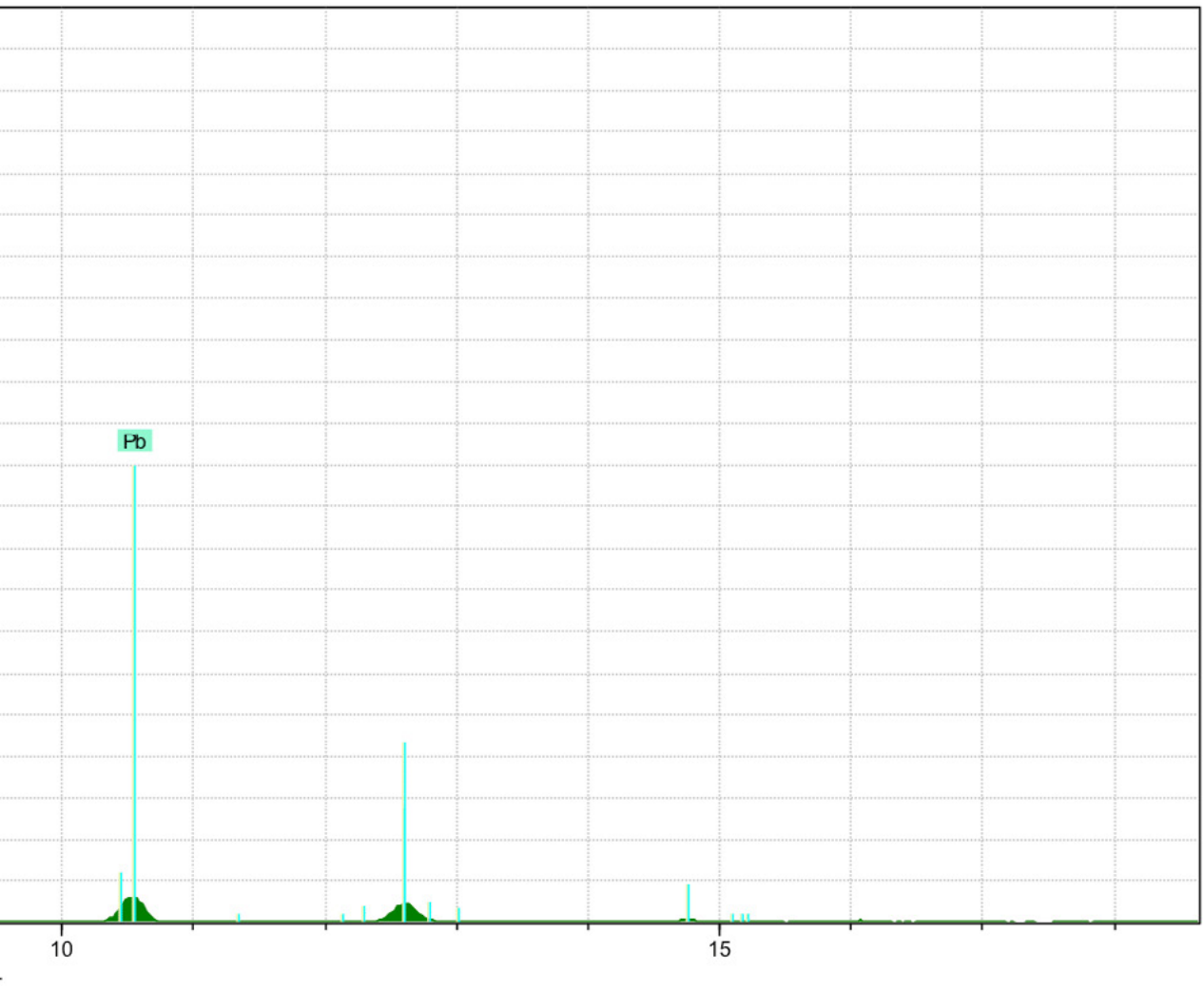
4.5 µA

air

filter: no

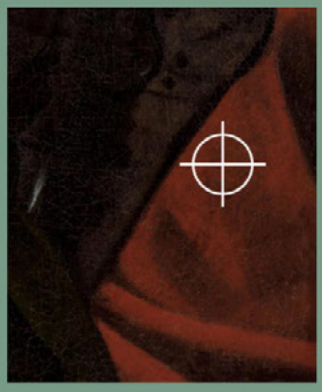
time: 120 seconds




Pb
10
15

Location 19

Red garment of the figure on the far right



Notes / possible pigments

Iron-based pigment, confirmed as hematite by Raman spectroscopy; lead white; copper-based pigment; chalk; umber

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Manganese (Mn)
	Copper (Cu)	Potassium (K)
	Lead (Pb)	Titanium (Ti)

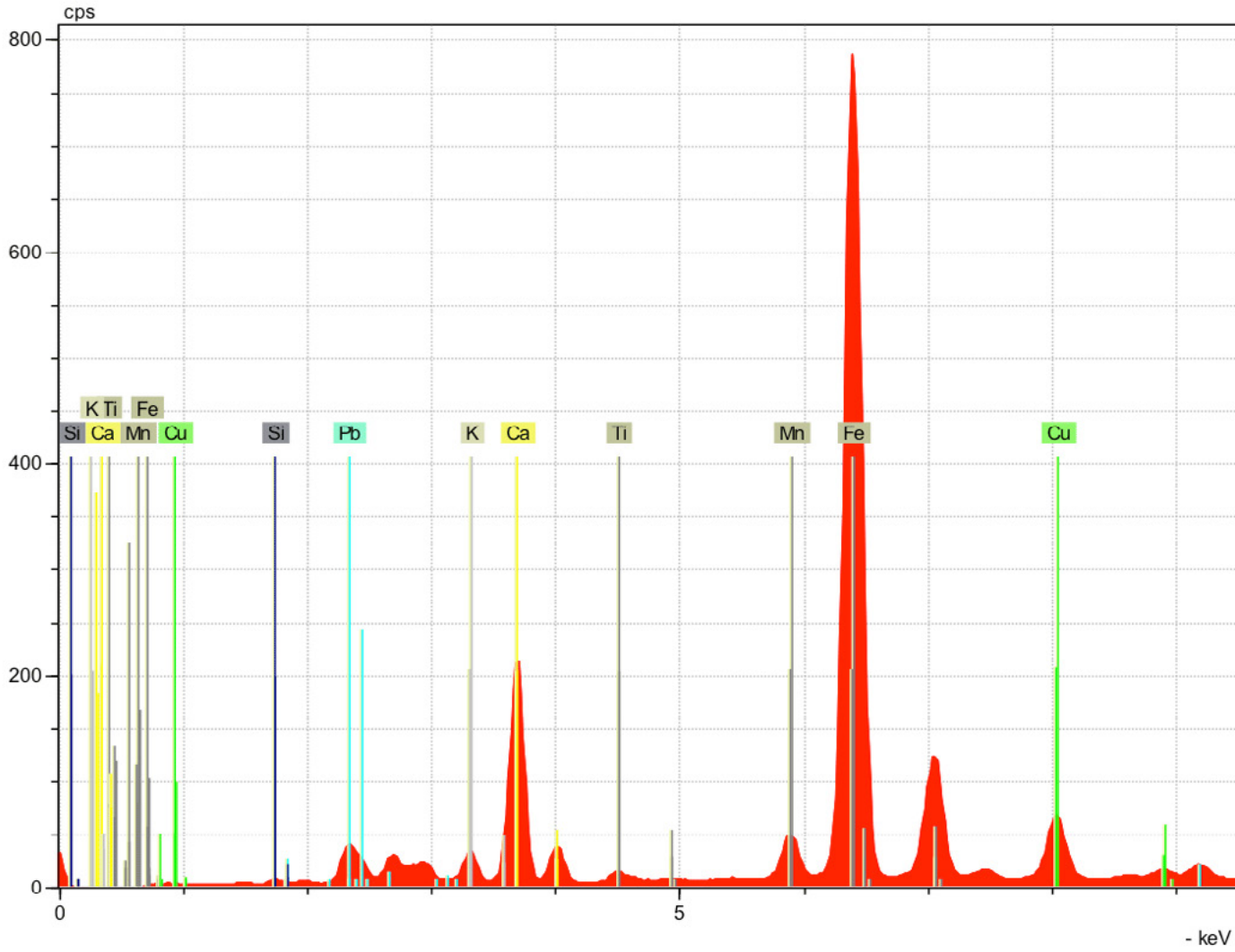
40 kV

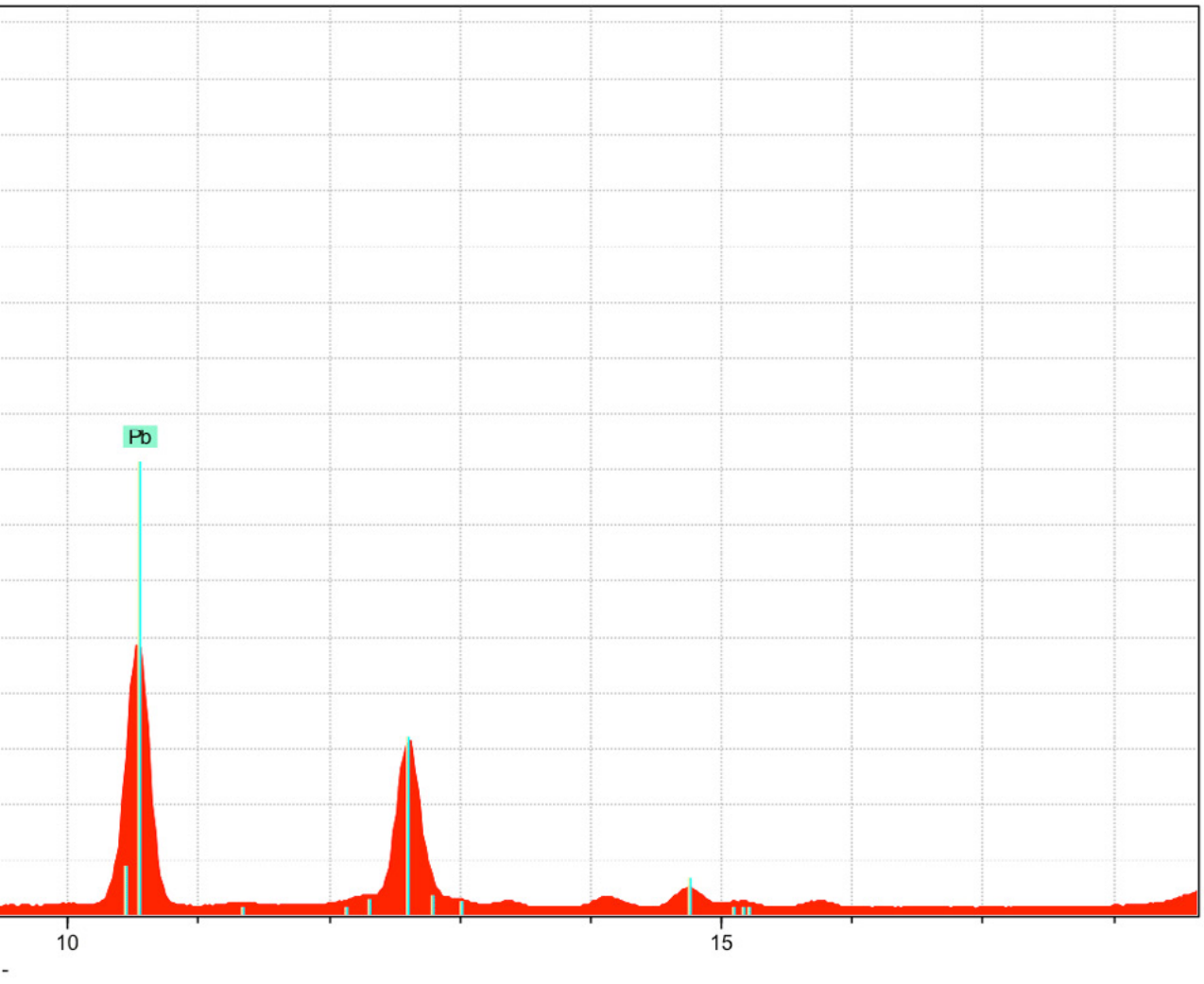
4.5 µA

air

filter: no

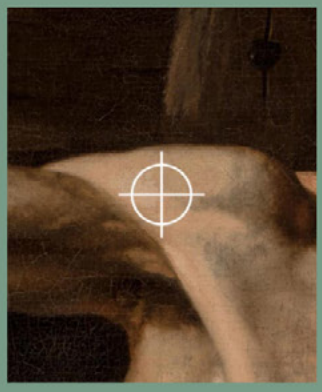
time: 120 seconds




Pb
10
15

Location 20

Highlight on Saint Andrew's shoulder, near cross section 7 (CS07)



Notes / possible pigments

Lead white; ochre pigments; chalk

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)

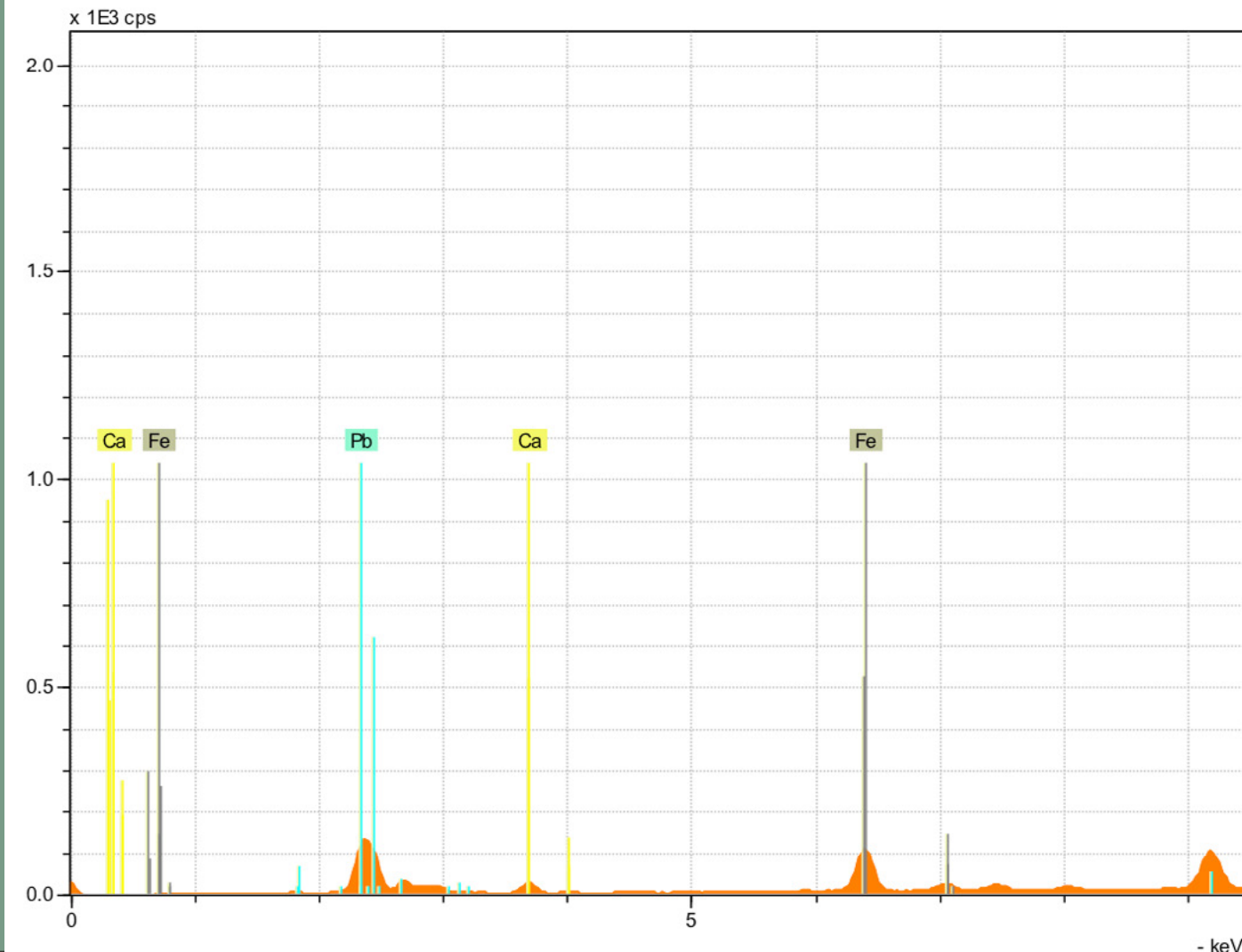
40 kV

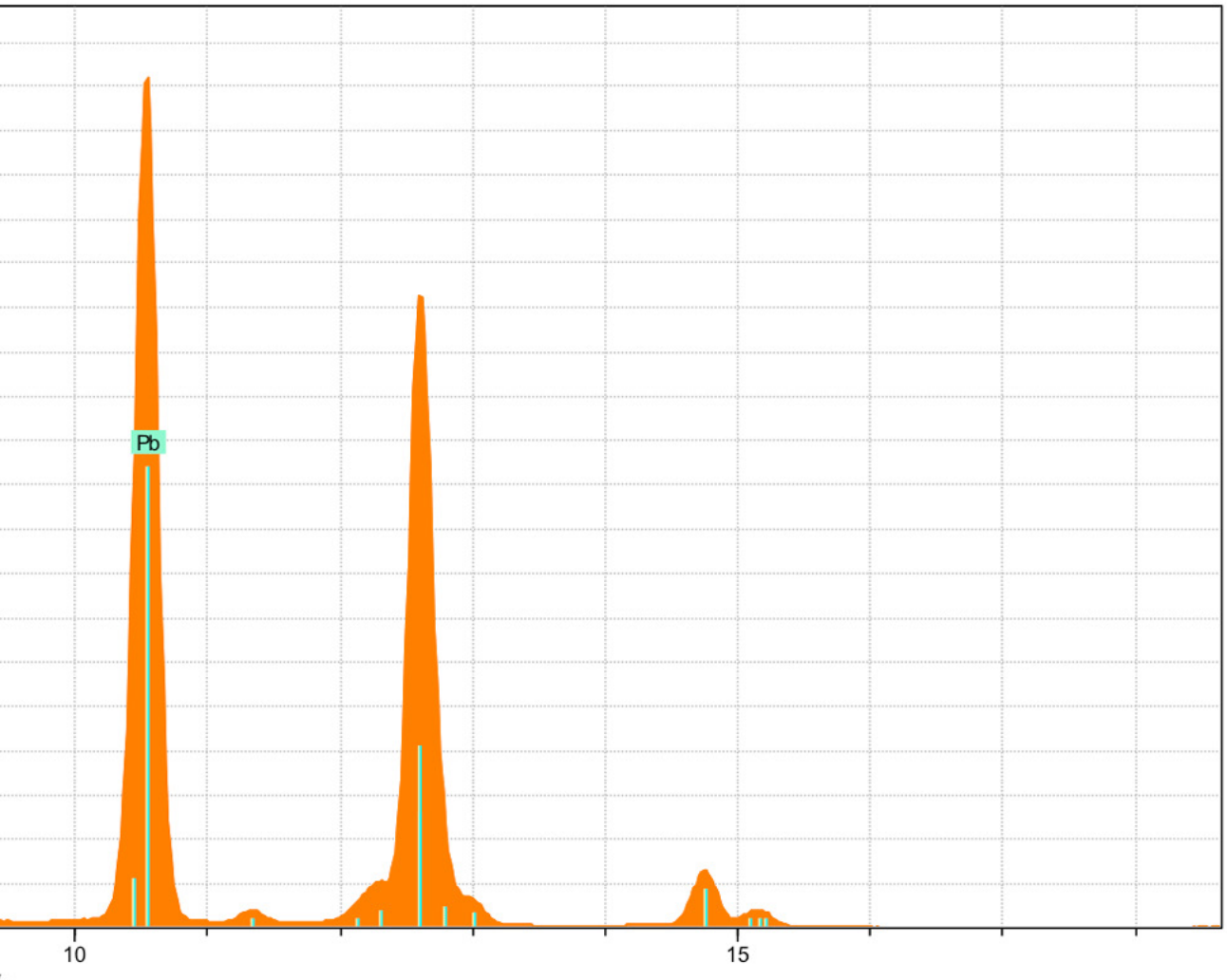
4.5 µA

air

filter: no

time: 120 seconds




Pb
10
15

Location 22a

Background to the left

Notes / possible pigments

Ochre pigments; umber; chalk

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Copper (Cu)
	Lead (Pb)	Potassium (K)
	Manganese (Mn)	Silicon (Si)

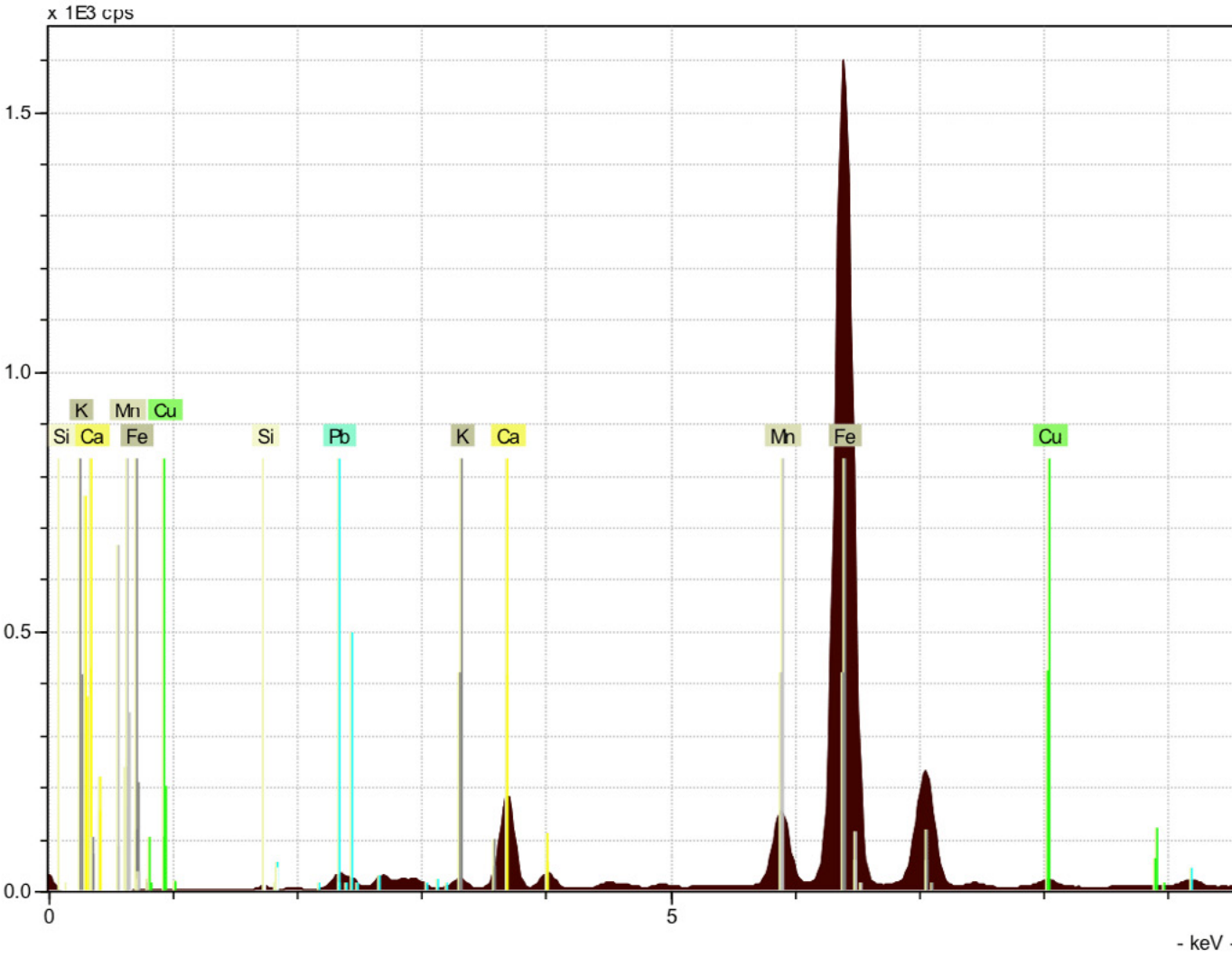
40 kV

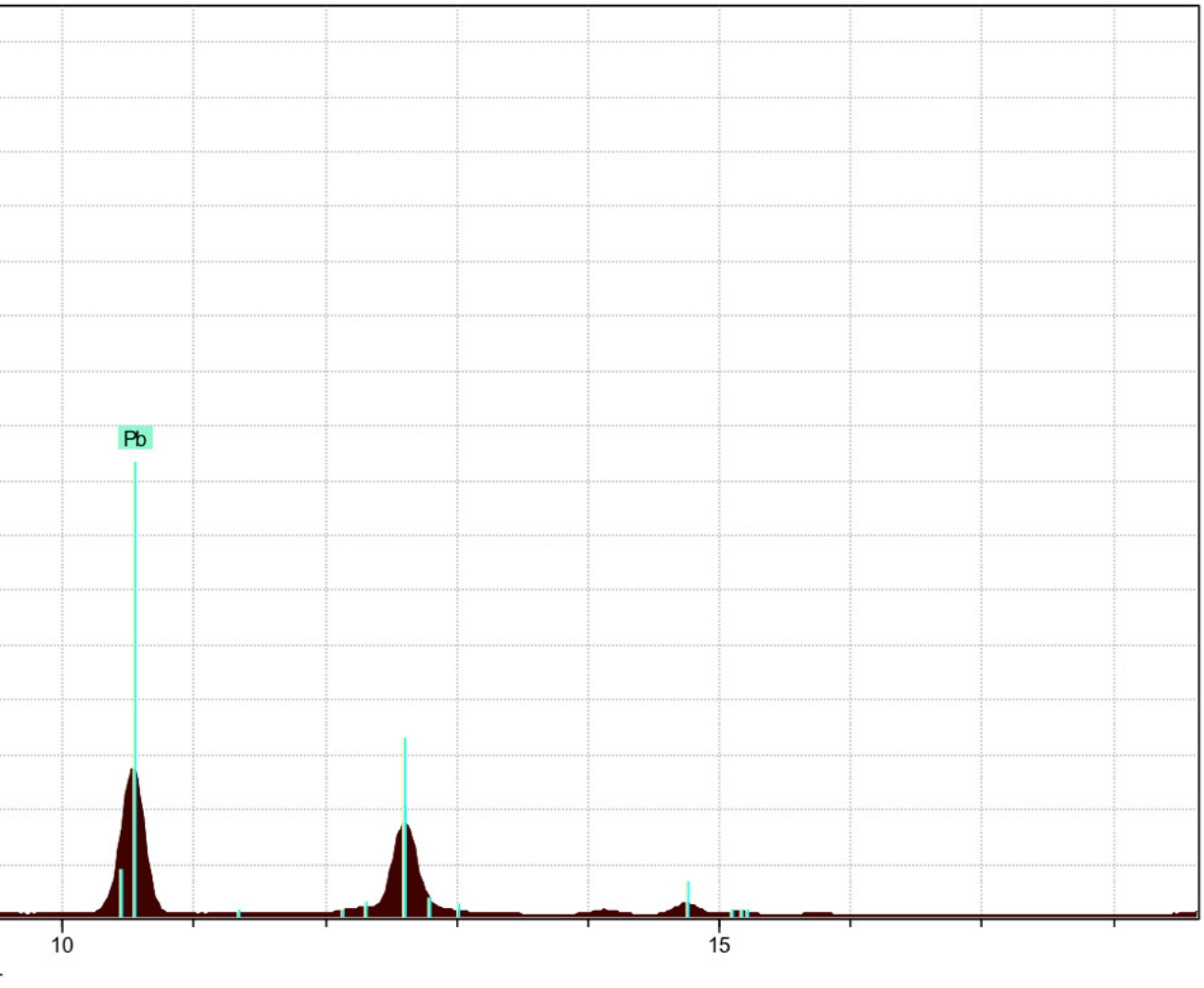
4.5 µA

air

filter: no

time: 120 seconds




Pb
10
15

Location 22b

Background to the left

Notes / possible pigments

Ochre pigments; umber; chalk; aluminosilicates

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Aluminum (Al)
	Lead (Pb)	Copper (Cu)
	Manganese (Mn)	Potassium (K)
		Silicon (Si)
		Titanium (Ti)

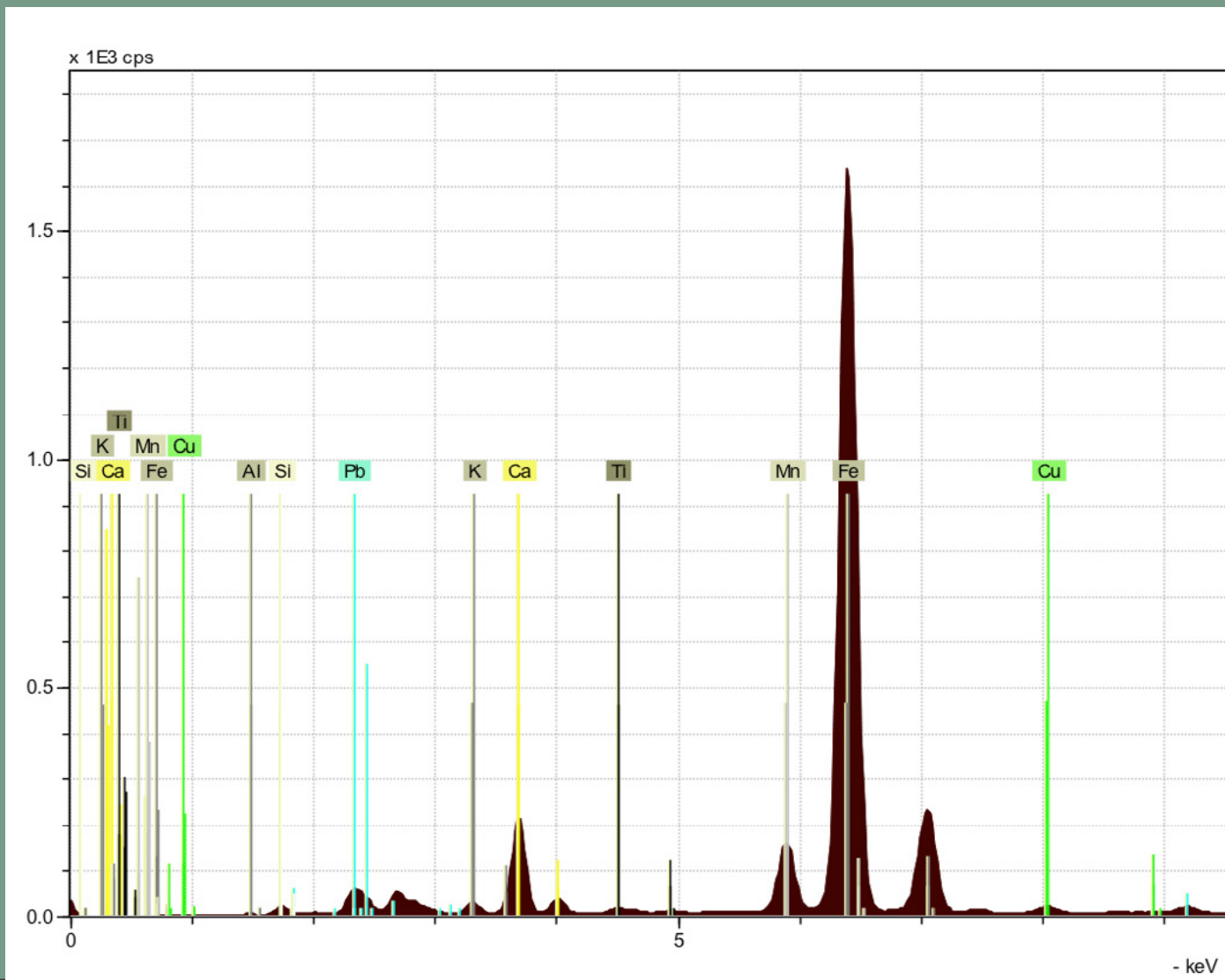
40 kV

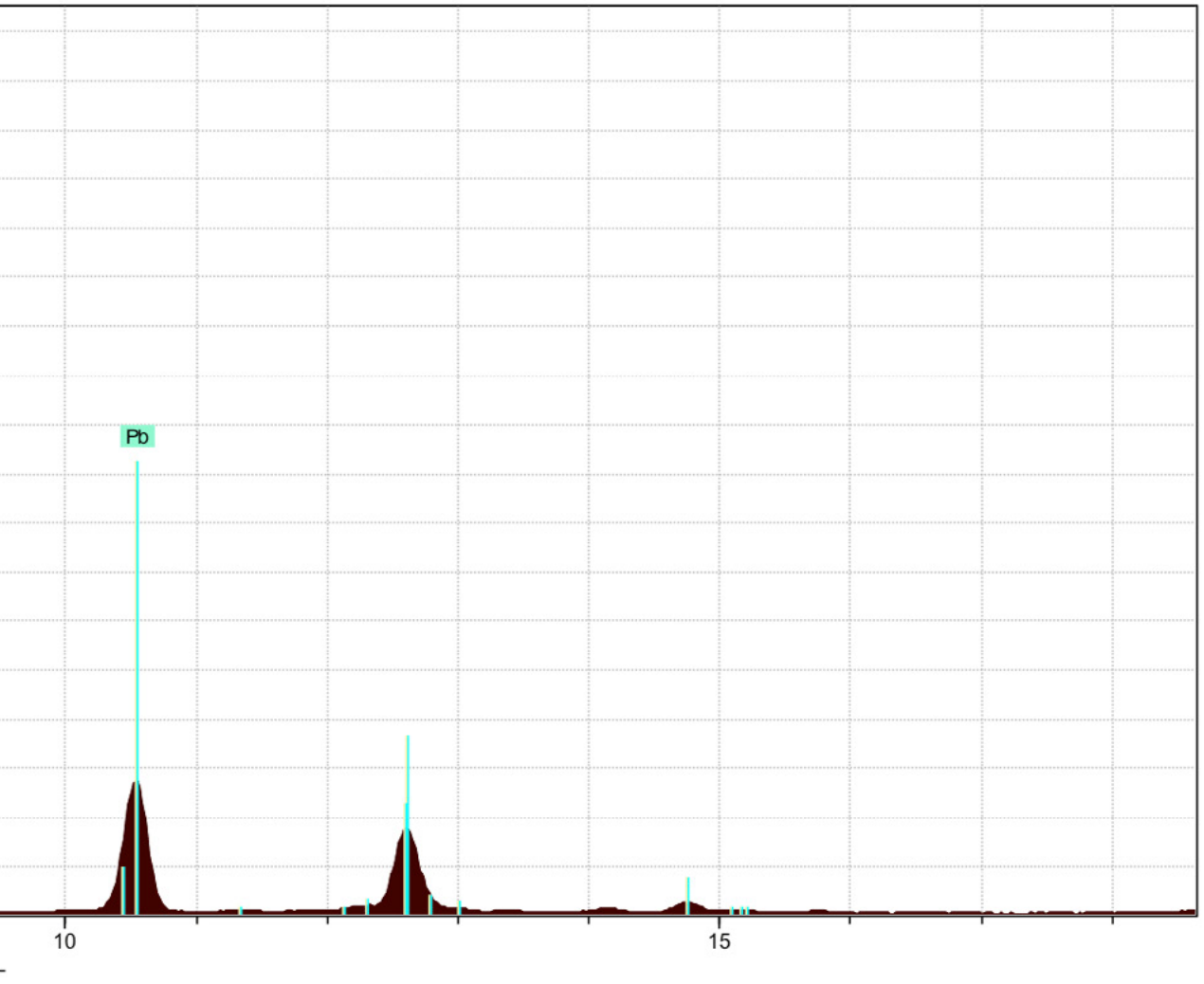
4.5 µA

vacuum

filter: no

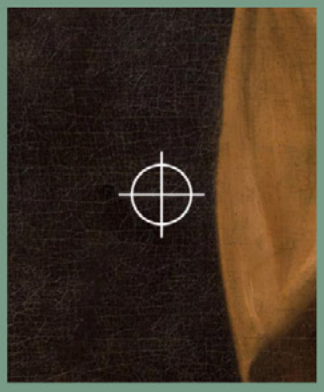
time: 120 seconds




Pb
10
15

Location 24a

Background to the left

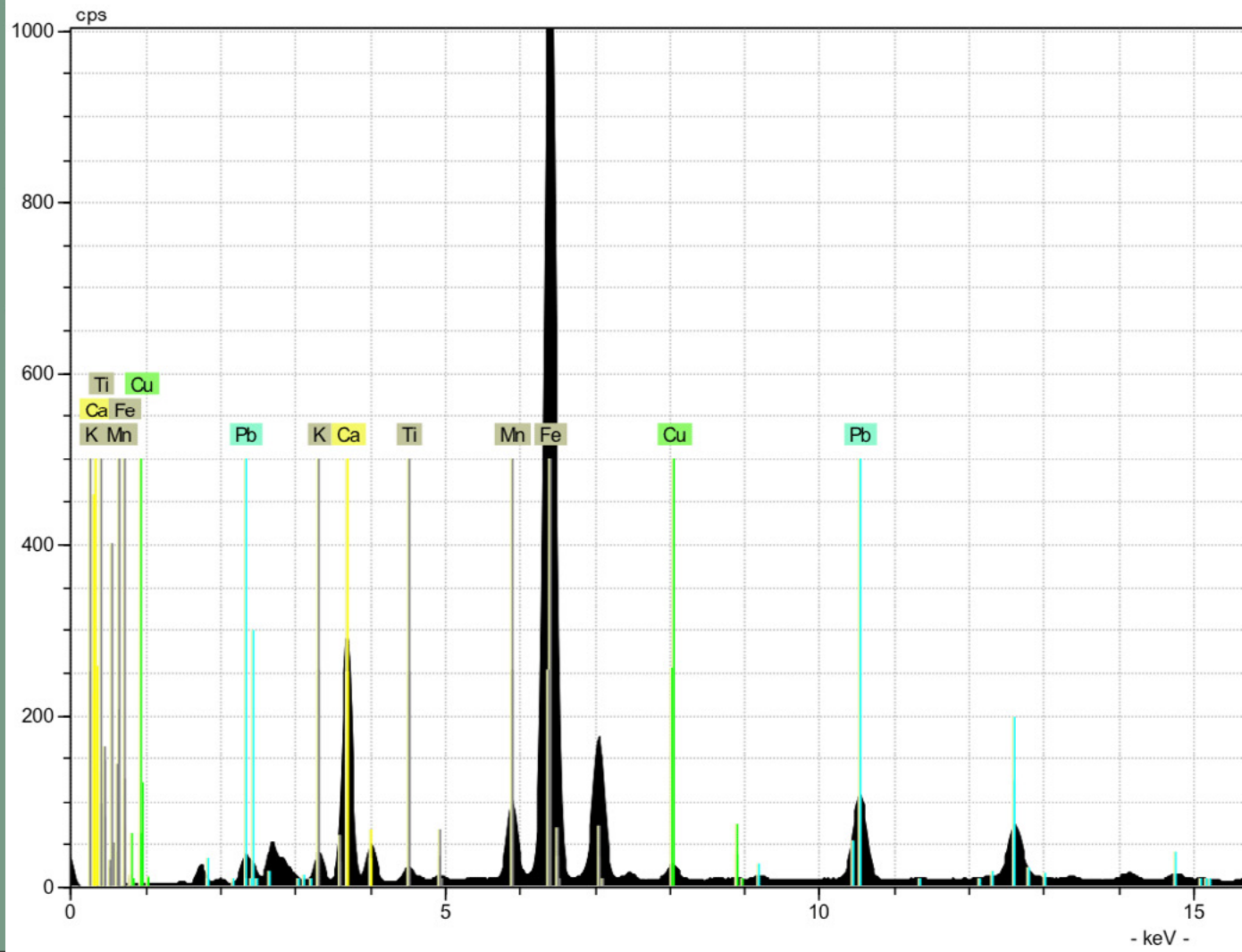


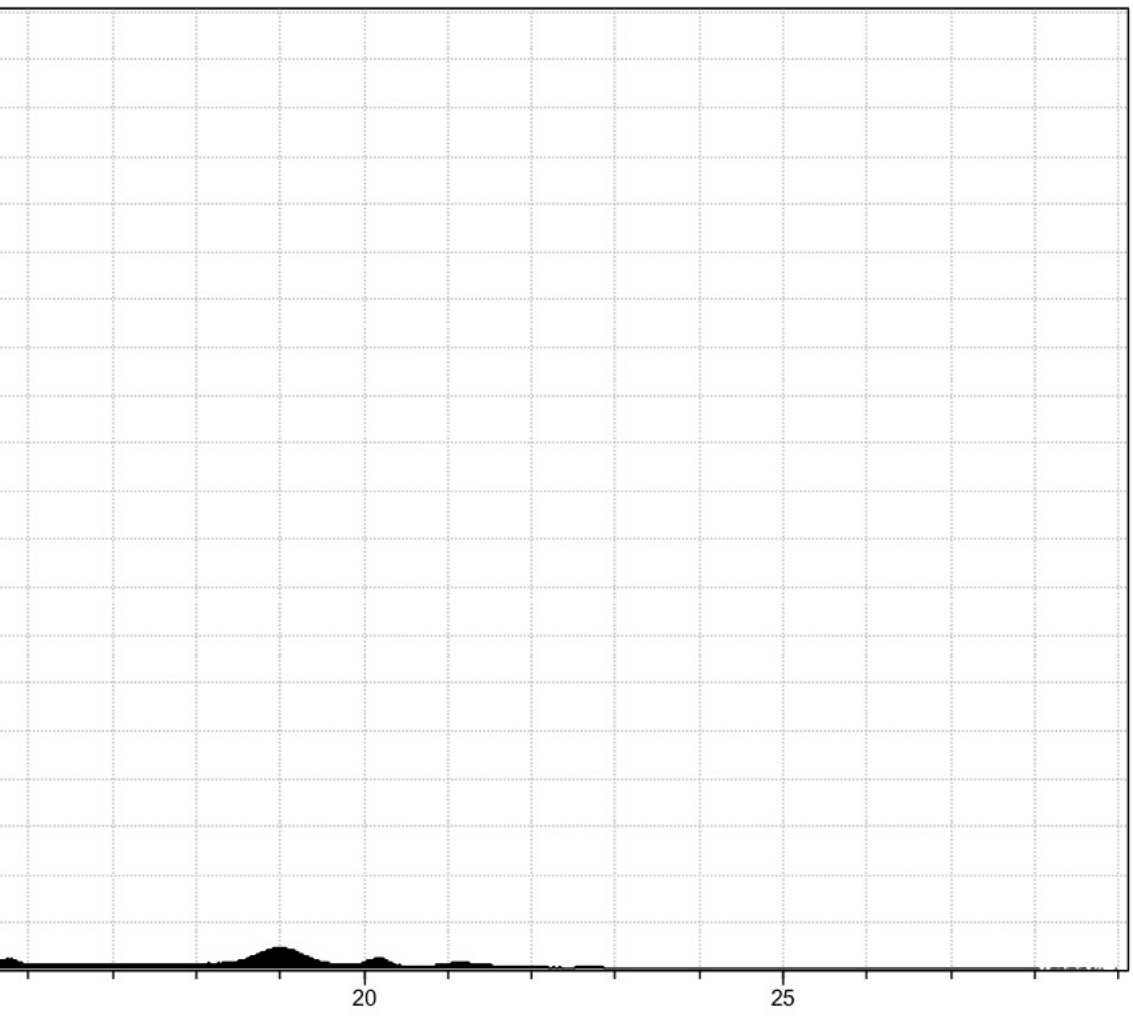
Notes / possible pigments

Iron-based pigments; umber;
lead white; chalk; aluminosilicates

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Copper (Cu)
	Lead (Pb)	Potassium (K)
	Manganese (Mn)	Silicon (Si)

40 kV
4.5 µA
vacuum
filter: no
time: 120 seconds




20
25

Location 24b

Background to the left

Notes / possible pigments

Iron-based pigment; umber; chalk

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Lead (Pb)
	Manganese (Mn)	Potassium (K)
		Titanium (Ti)

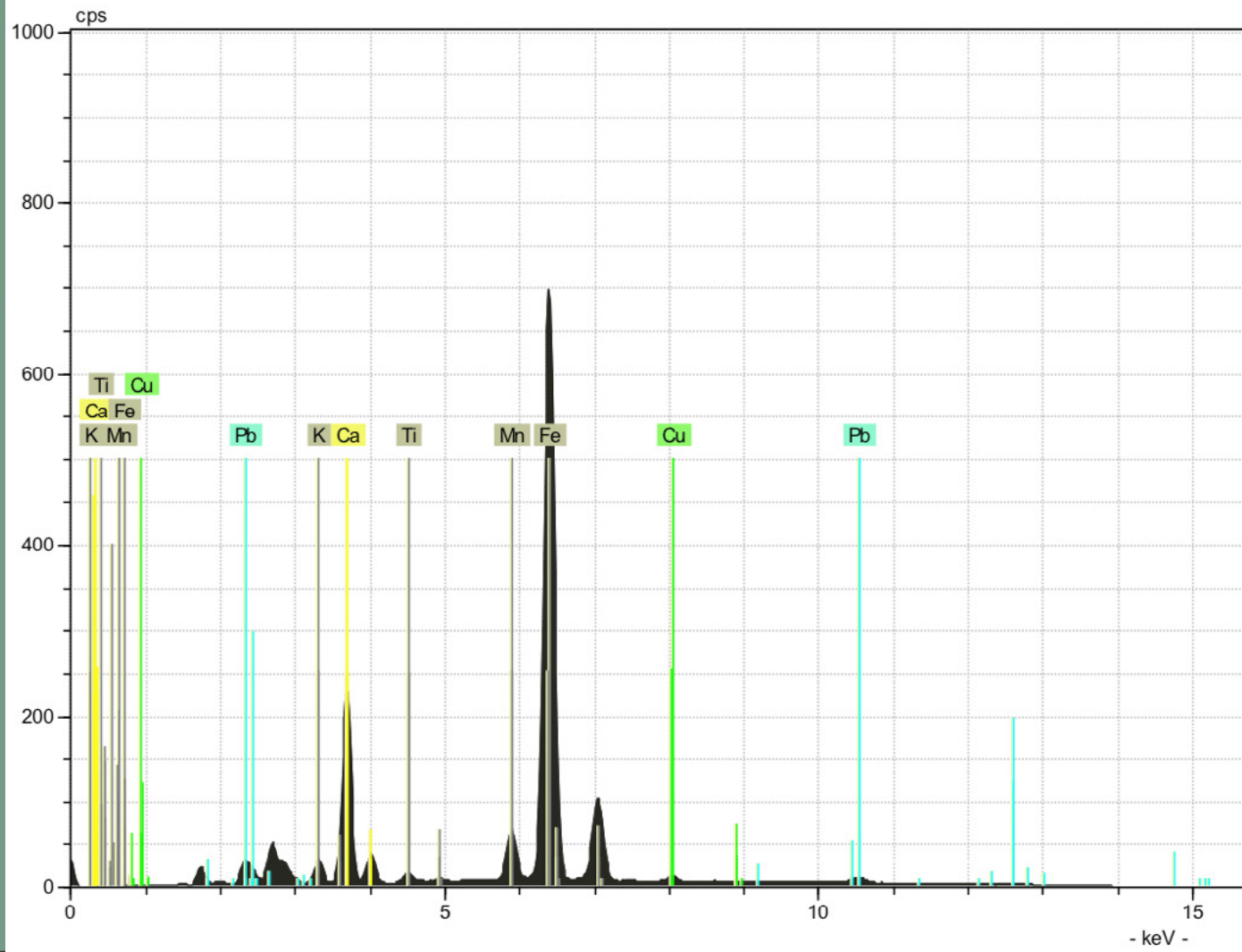
15 kV

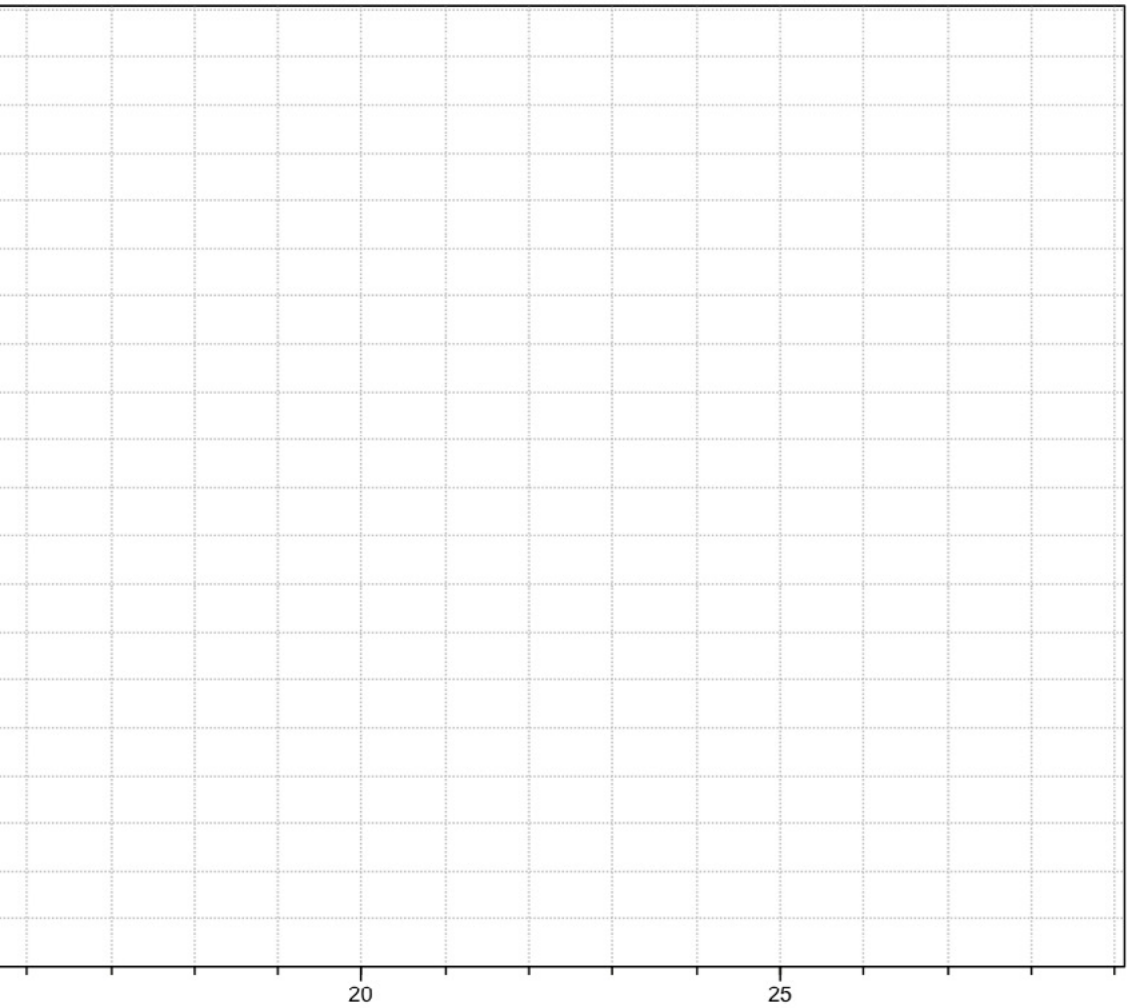
10 µA

vacuum

filter: no

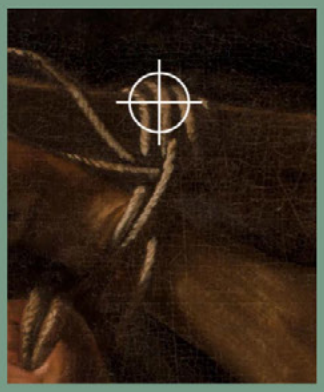
time: 120 seconds




20
25

Location 26

Ropes around Saint Andrew's right arm

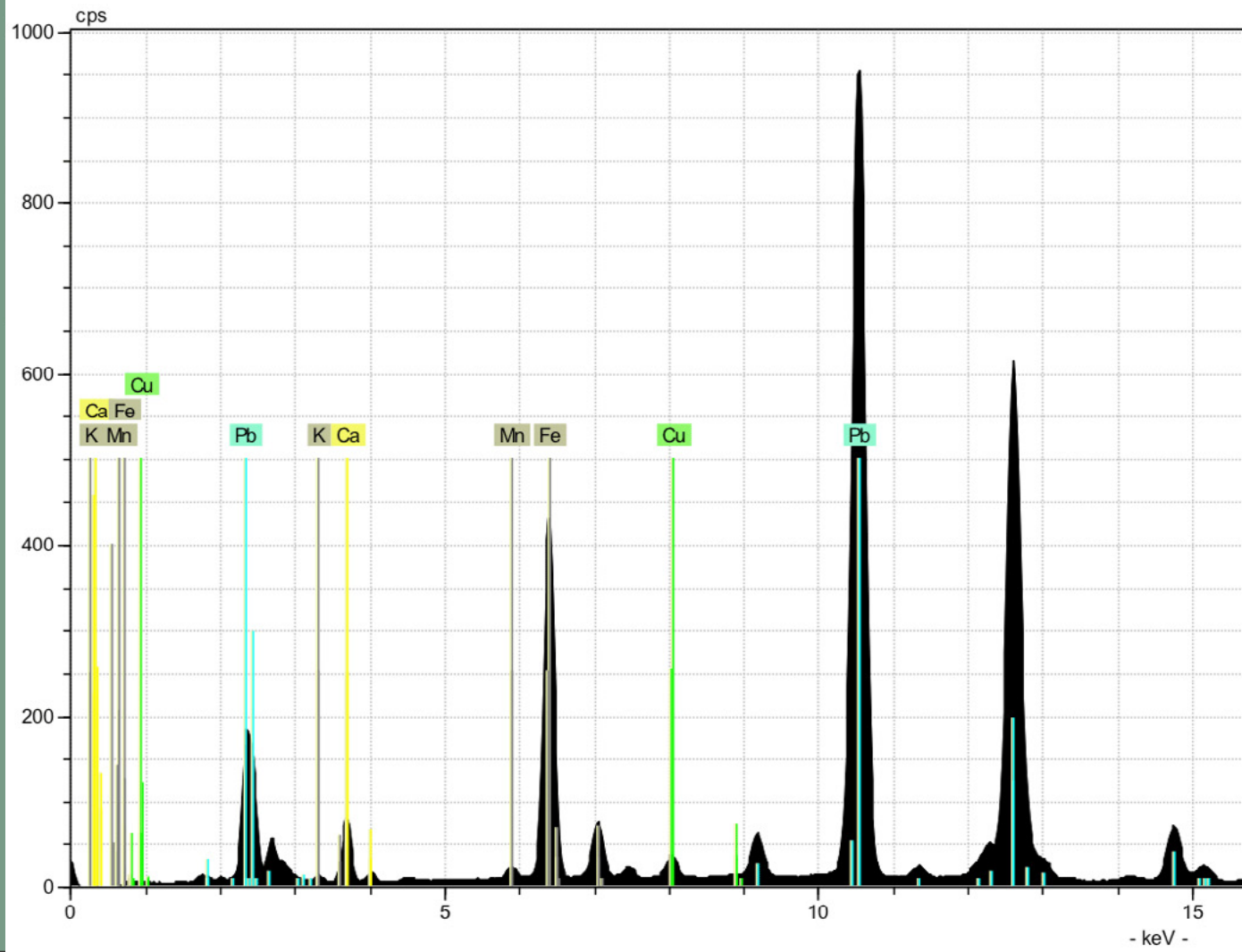


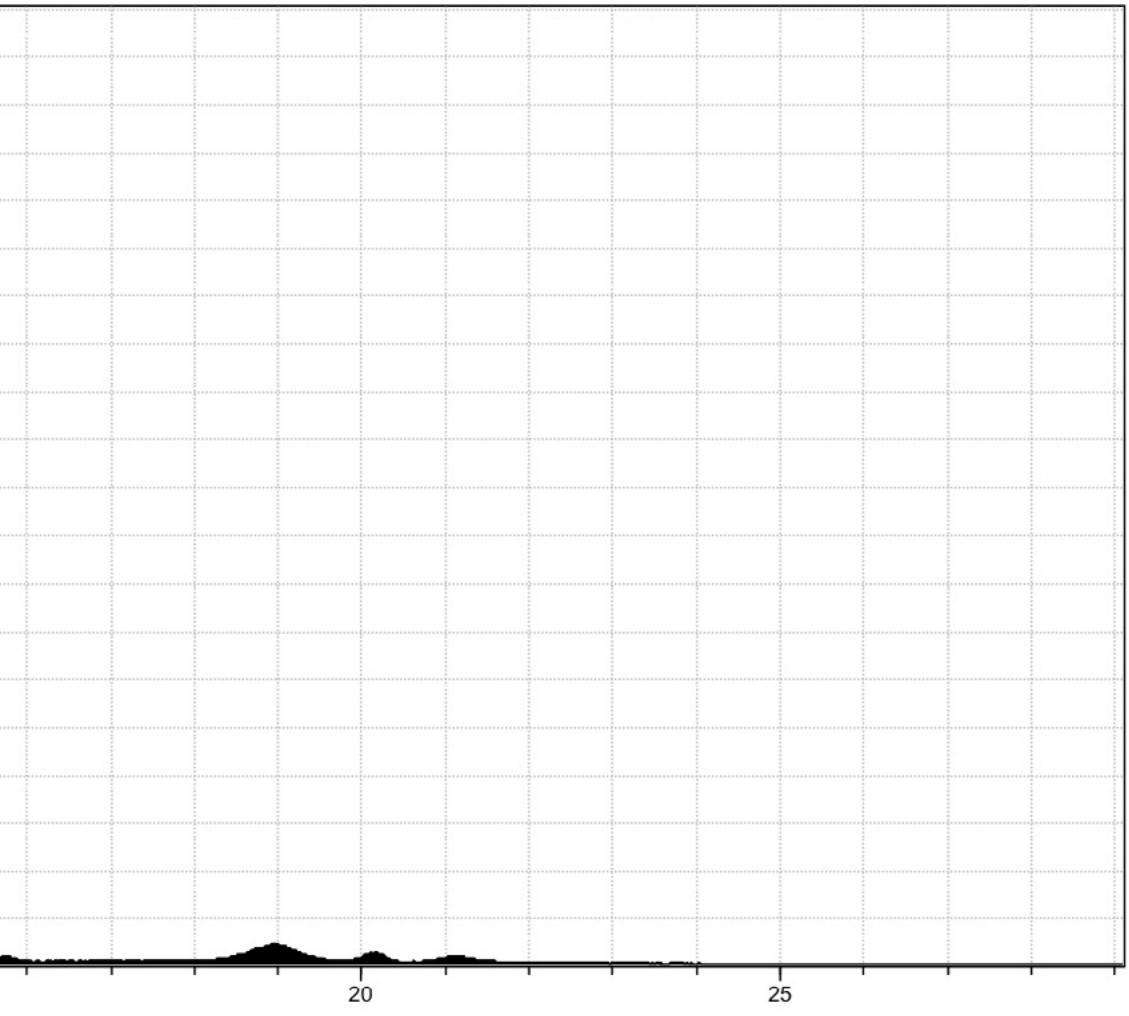
Notes / possible pigments

Lead white; copper-based pigment; iron-based pigment

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Calcium (Ca)	Copper (Cu)
	Iron (Fe)	Manganese (Mn)
		Potassium (K)

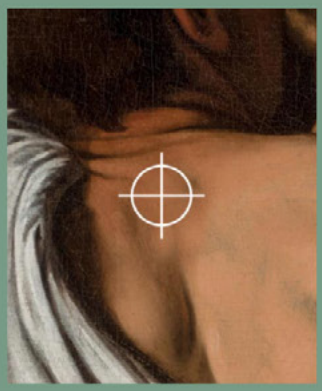
40 kV
4.5 µA
vacuum
filter: no
time: 120 seconds




20
25

Location 27a

Reddish area on the back of the executioner, near his neck

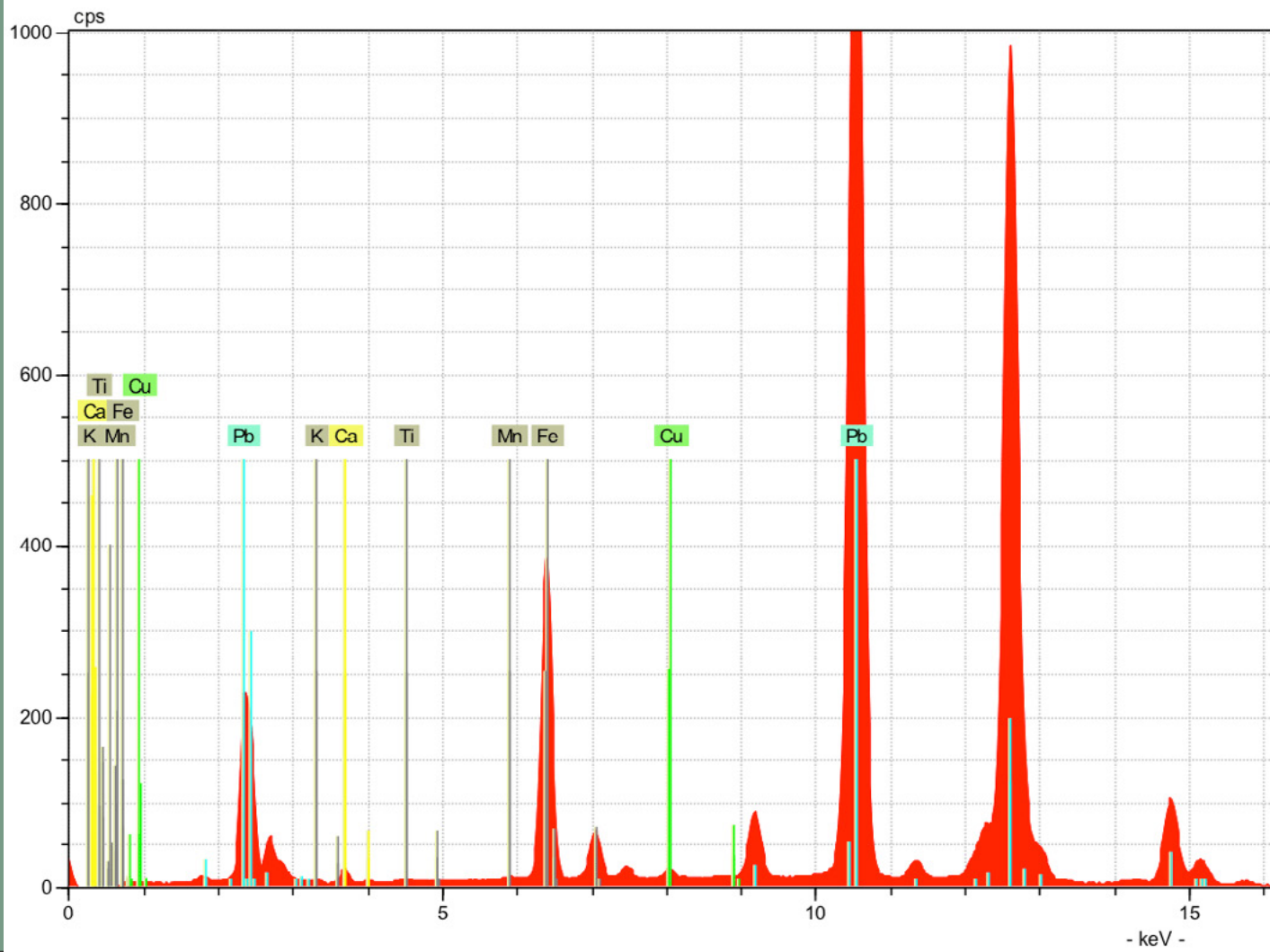


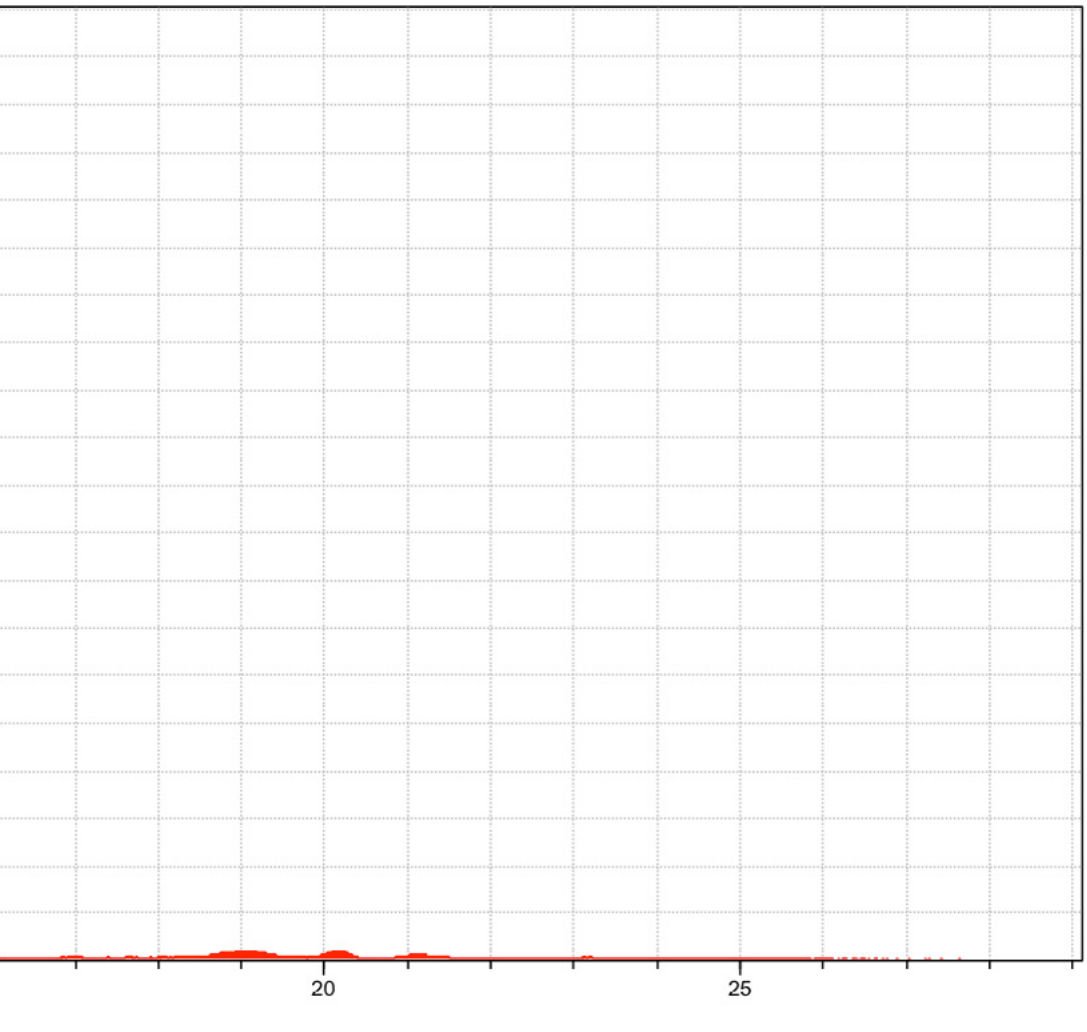
Notes / possible pigments

Lead white; ochre pigments

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)
		Copper (Cu)
		Potassium (K)

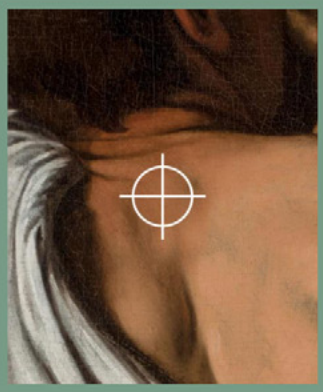
40 kV
4.5 µA
vacuum
filter: no
time: 120 seconds




20
25

Location 27b

Reddish area on the back of the executioner, near his neck



Notes / possible pigments

Lead white; ochre pigments

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)
		Copper (Cu)

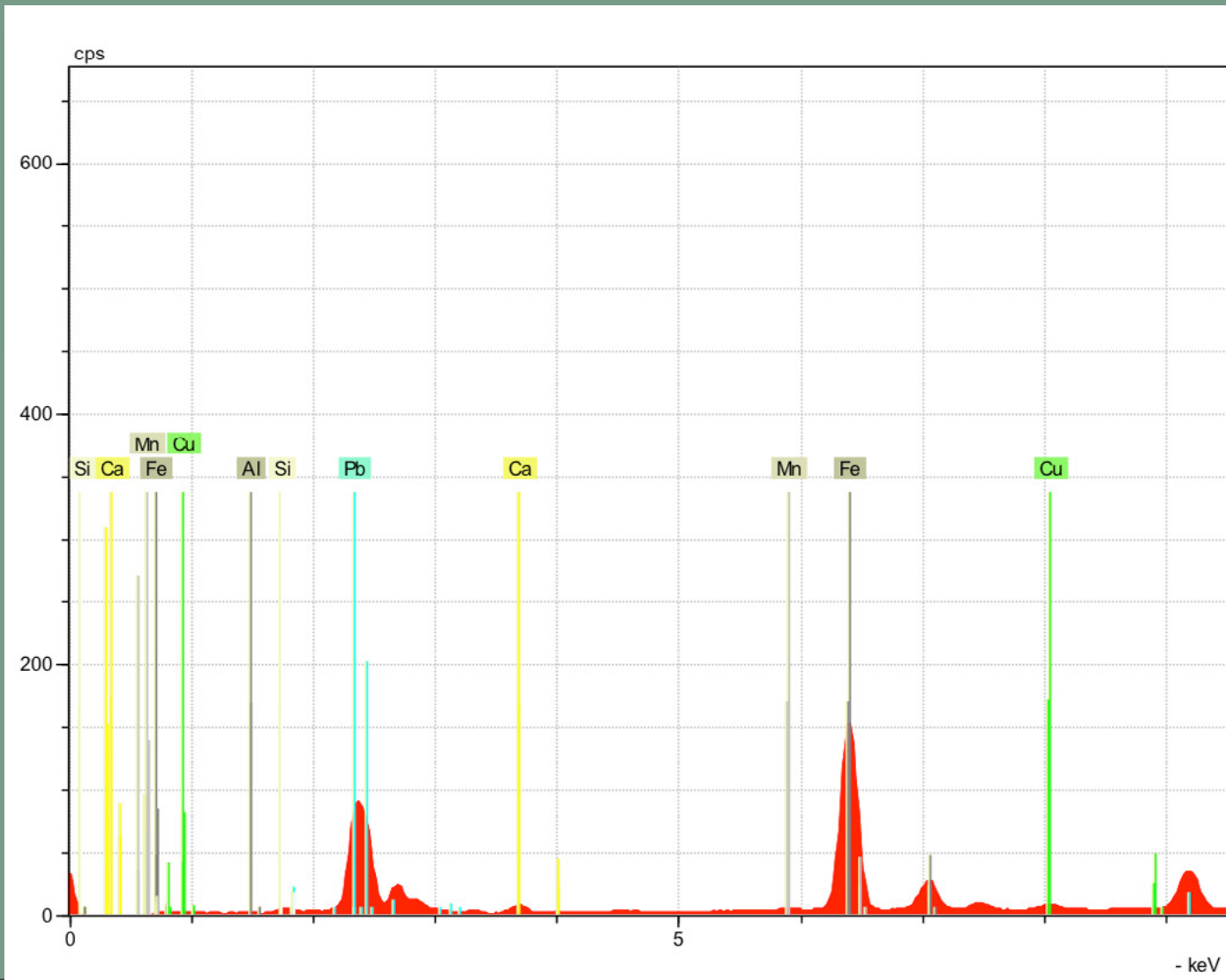
40 kV

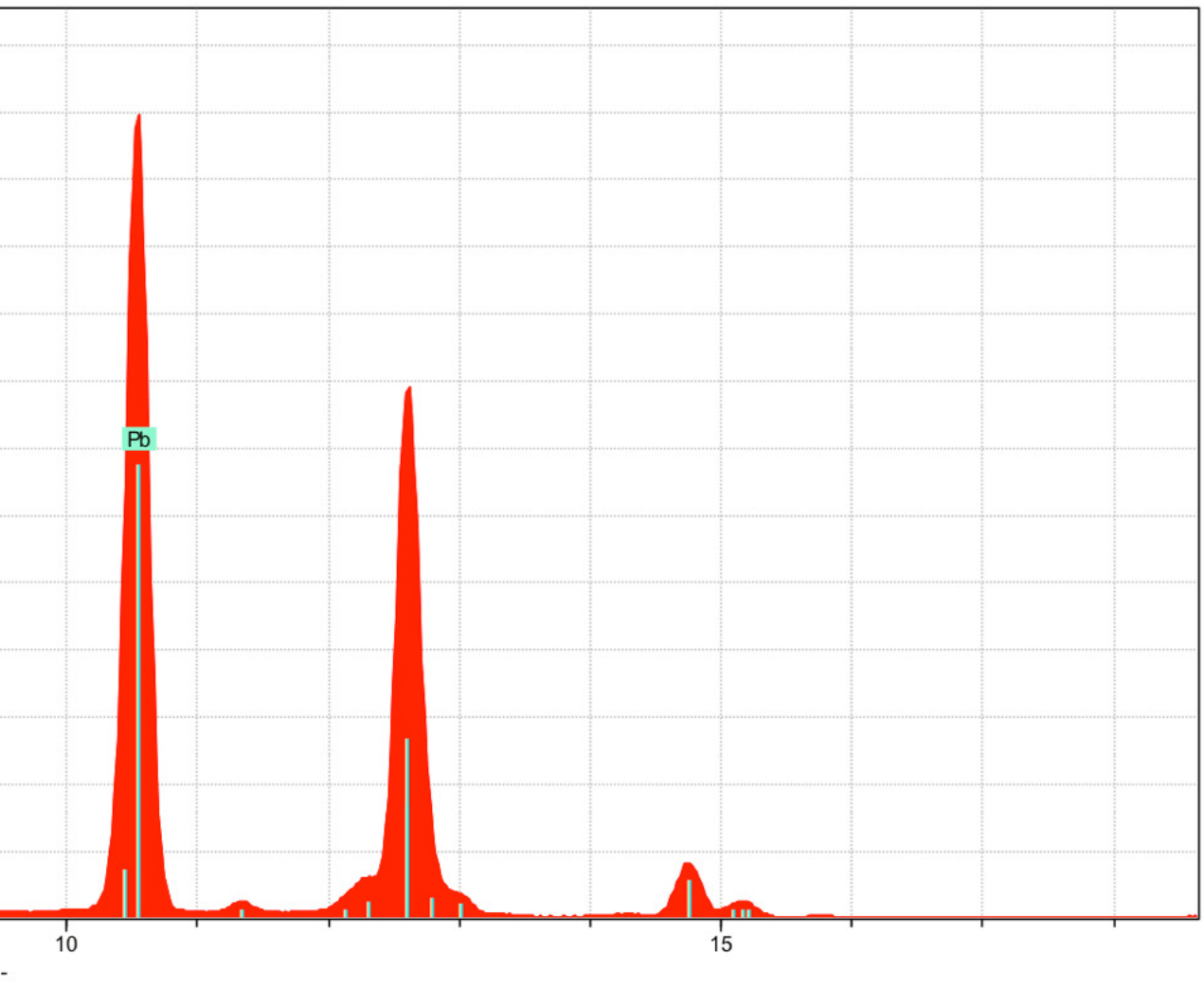
1.8 µA

vacuum

filter: no

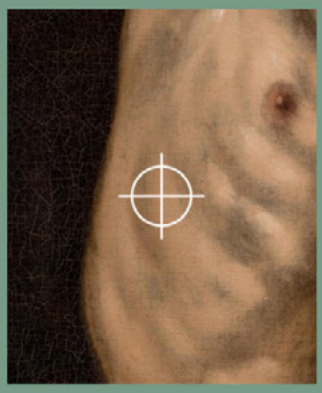
time: 120 seconds




Pb
10
15

Location 29

Saint Andrew's ribs



Notes / possible pigments

Lead white; iron-based pigment; chalk

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)
		Copper (Cu)

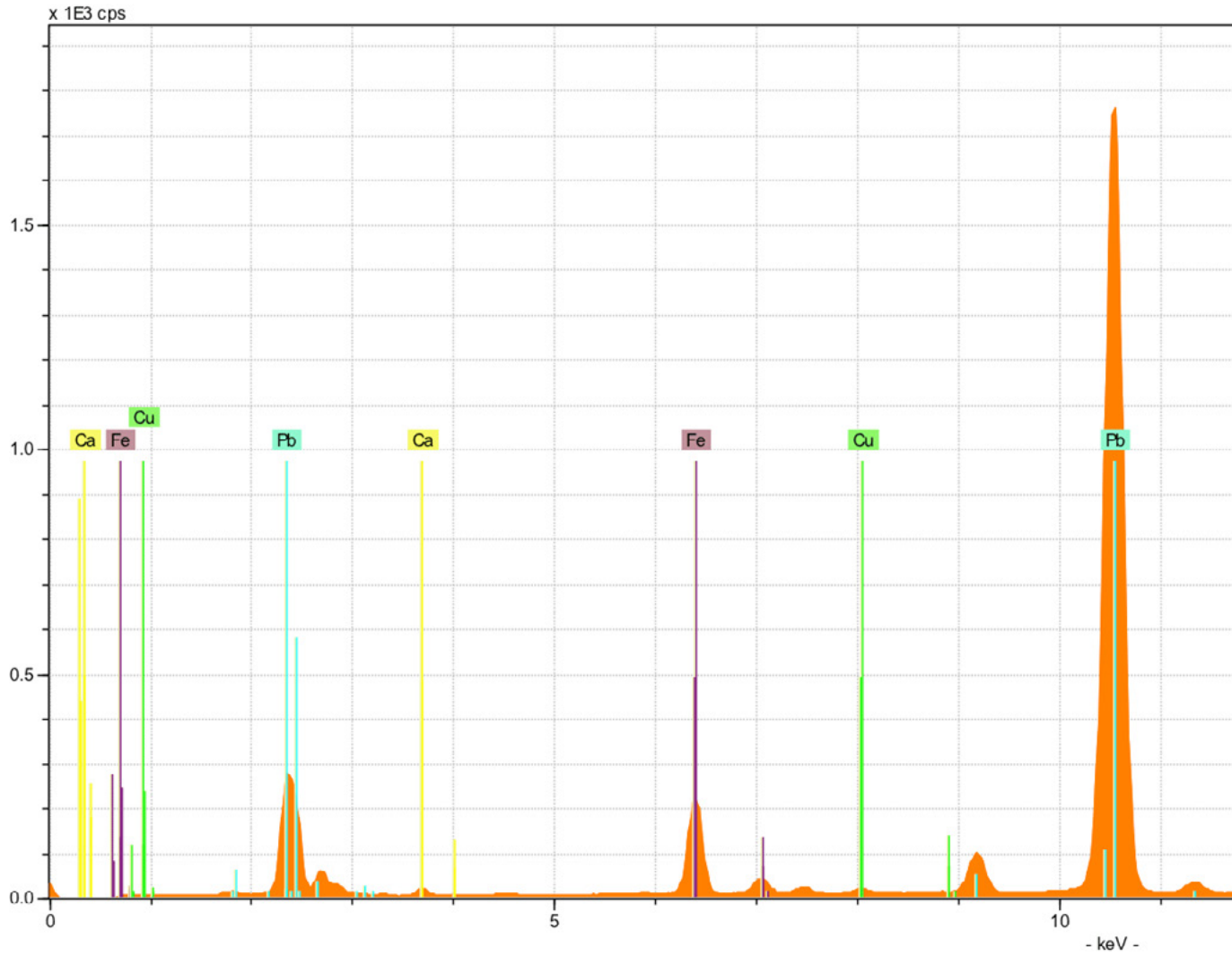
40 kV

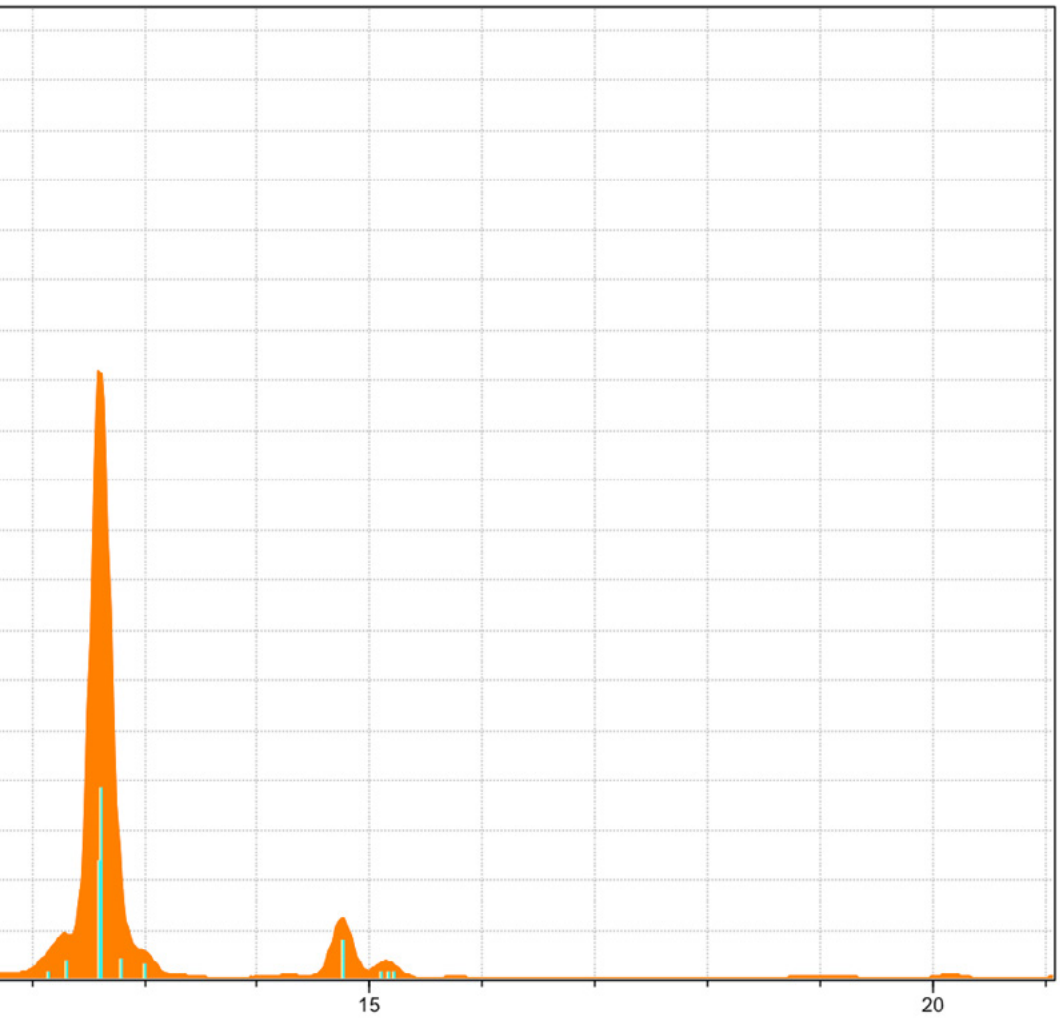
4.5 µA

vacuum

filter: no

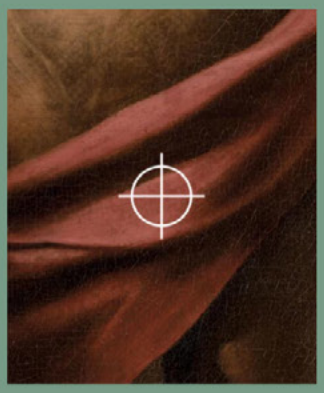
time: 120 seconds




15
20

Location 30

Saint Andrew's red garment



Notes / possible pigments

Lead white; iron-based pigment; vermilion

Major intensity	Minor intensity
Lead (Pb)	Calcium (Ca)
Mercury (Hg)	Copper (Cu)
	Iron (Fe)
	Potassium (K)

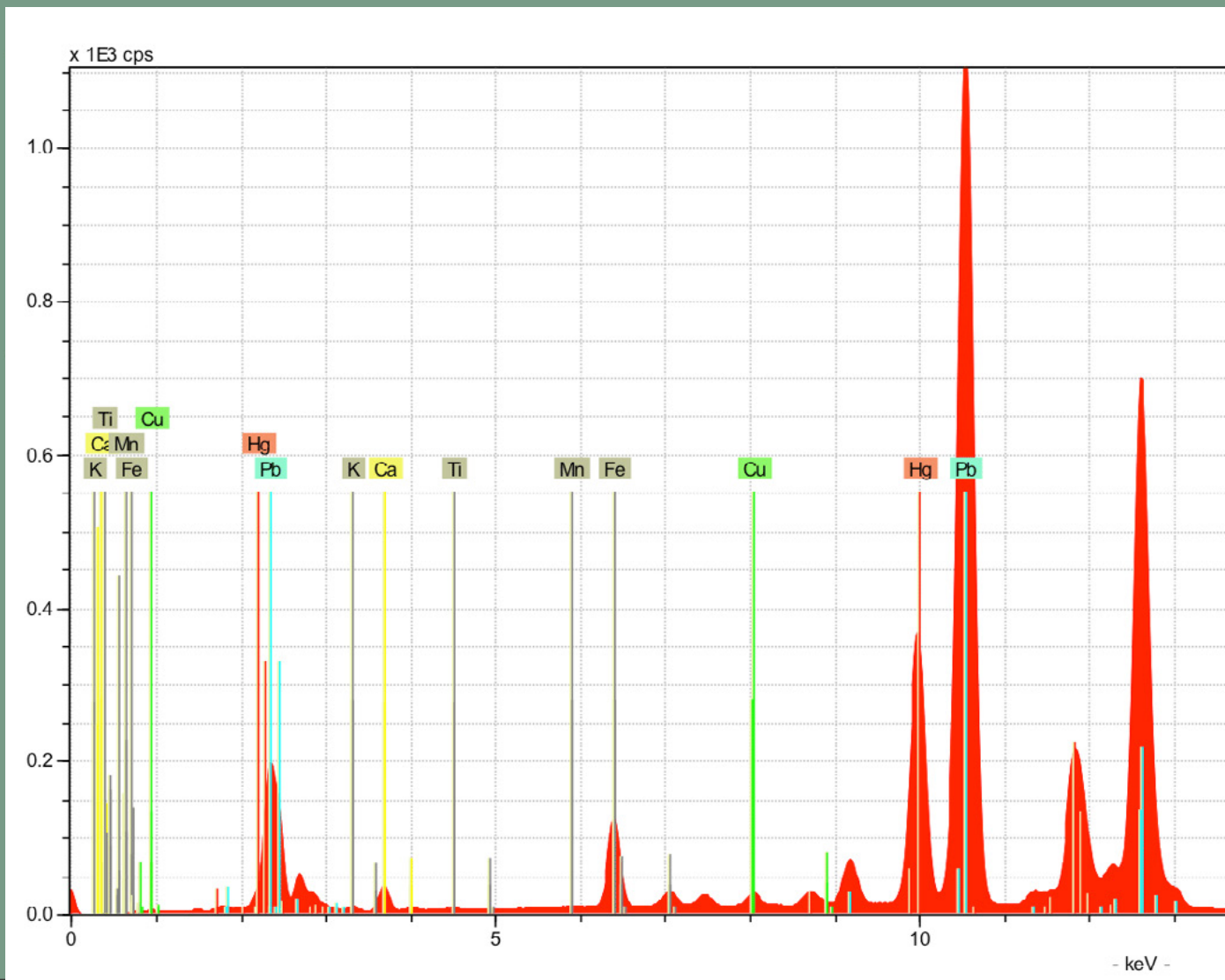
40 kV

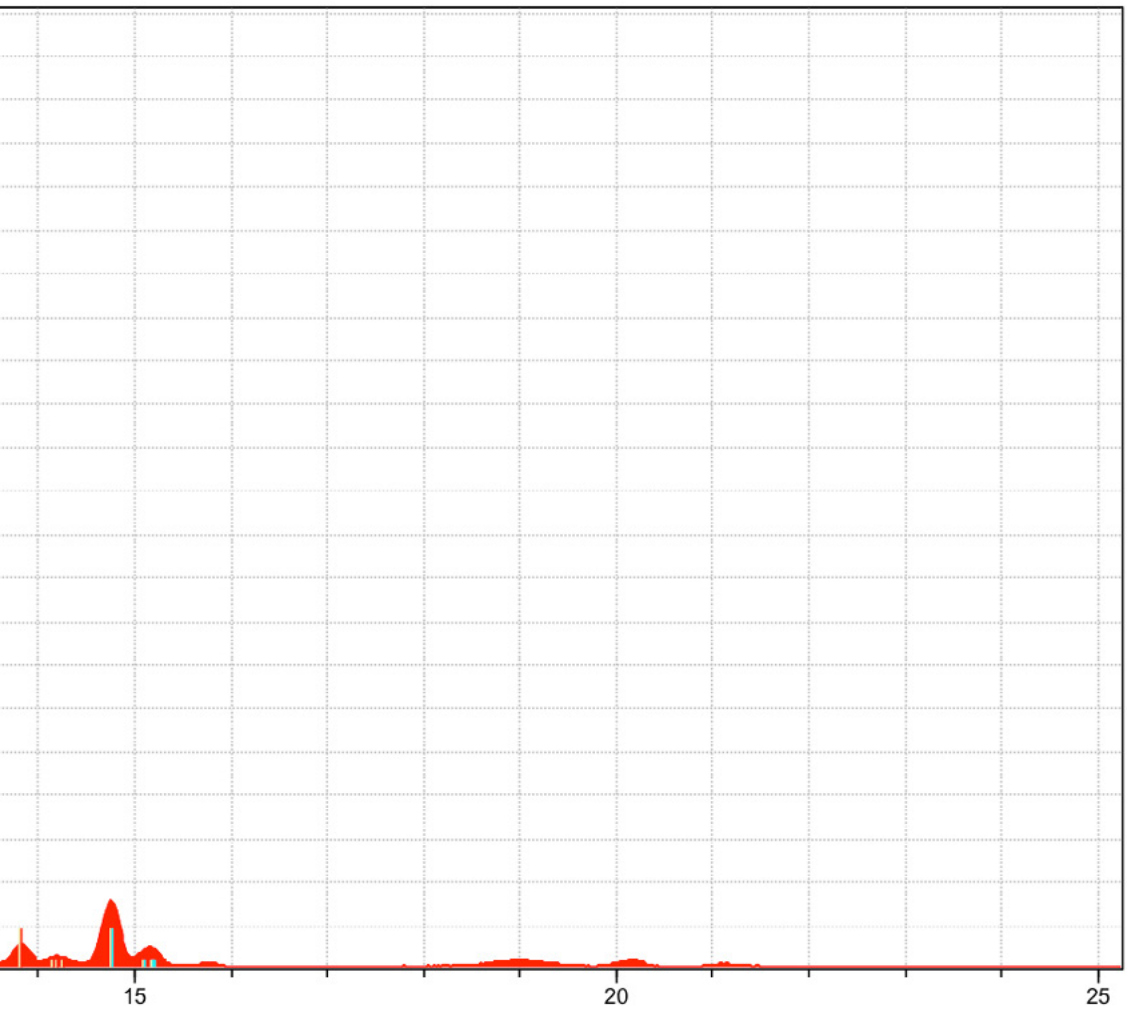
4.5 µA

vacuum

filter: no

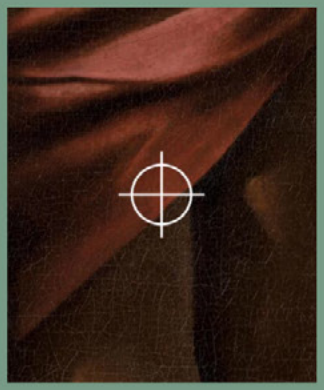
time: 120 seconds




15
20
25

Location 31

Edge of Saint Andrew's red garment



Notes / possible pigments

Vermilion; lead white; iron-based pigment; umber

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Manganese (Mn)
Lead (Pb)	Copper (Cu)	Potassium (K)
Mercury (Hg)		Titanium (Ti)

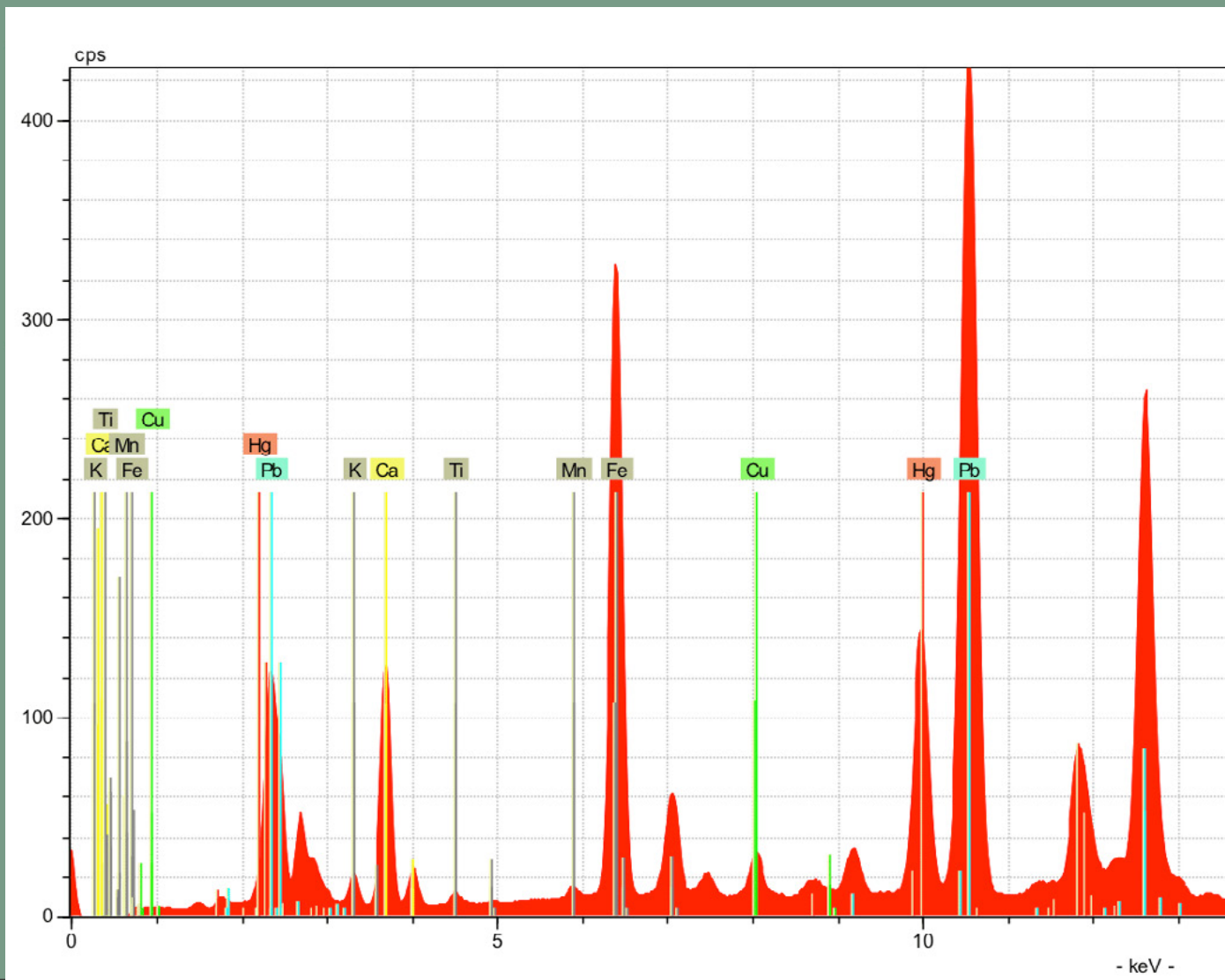
40 kV

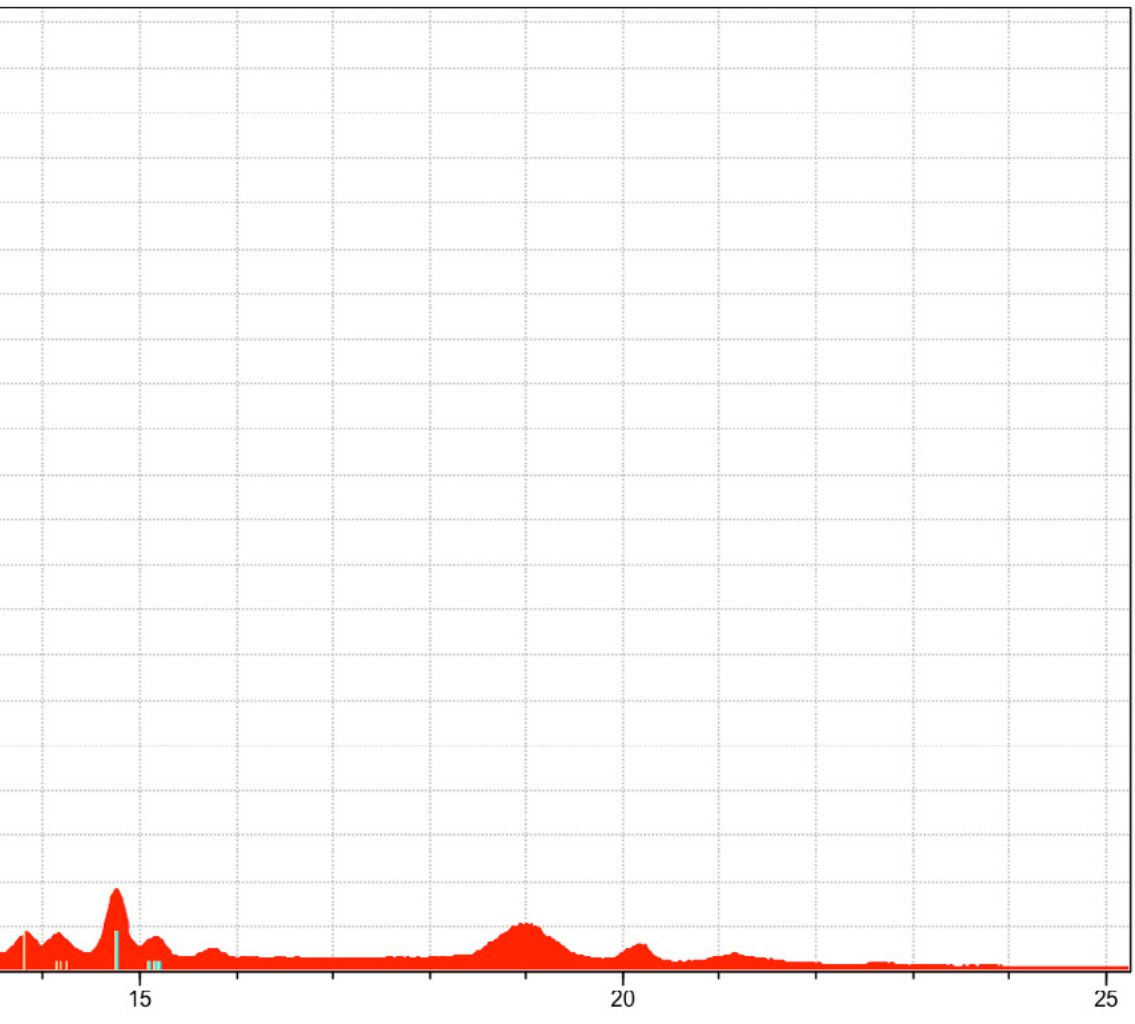
4.5 µA

vacuum

filter: no

time: 120 seconds




15
20
25

Location 32

Saint Andrew's leg in shadow below his garment

Notes / possible pigments

Iron-based pigment; lead white; umber; chalk

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Copper (Cu)
	Lead (Pb)	Potassium (K)
	Manganese (Mn)	Titanium (Ti)

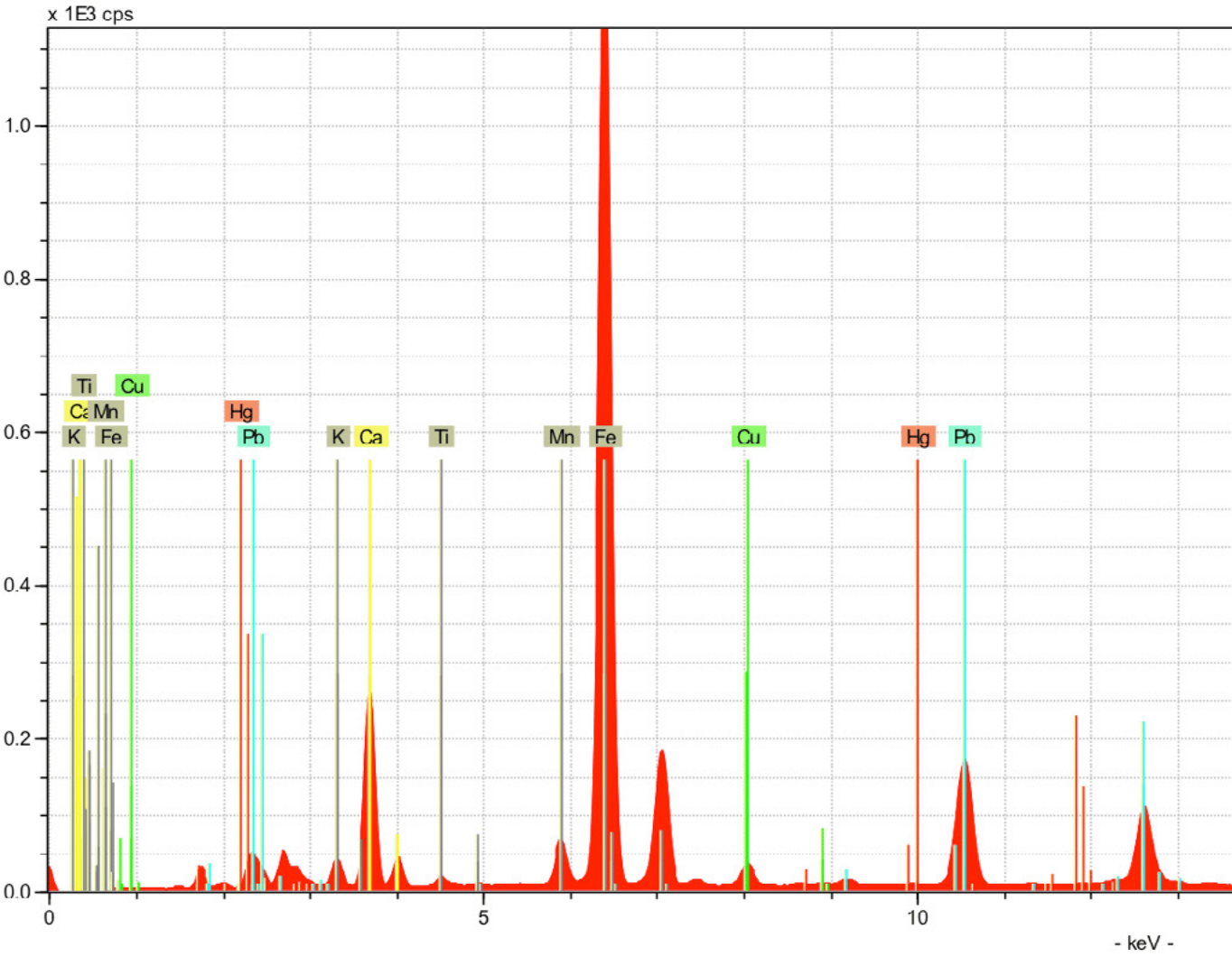
40 kV

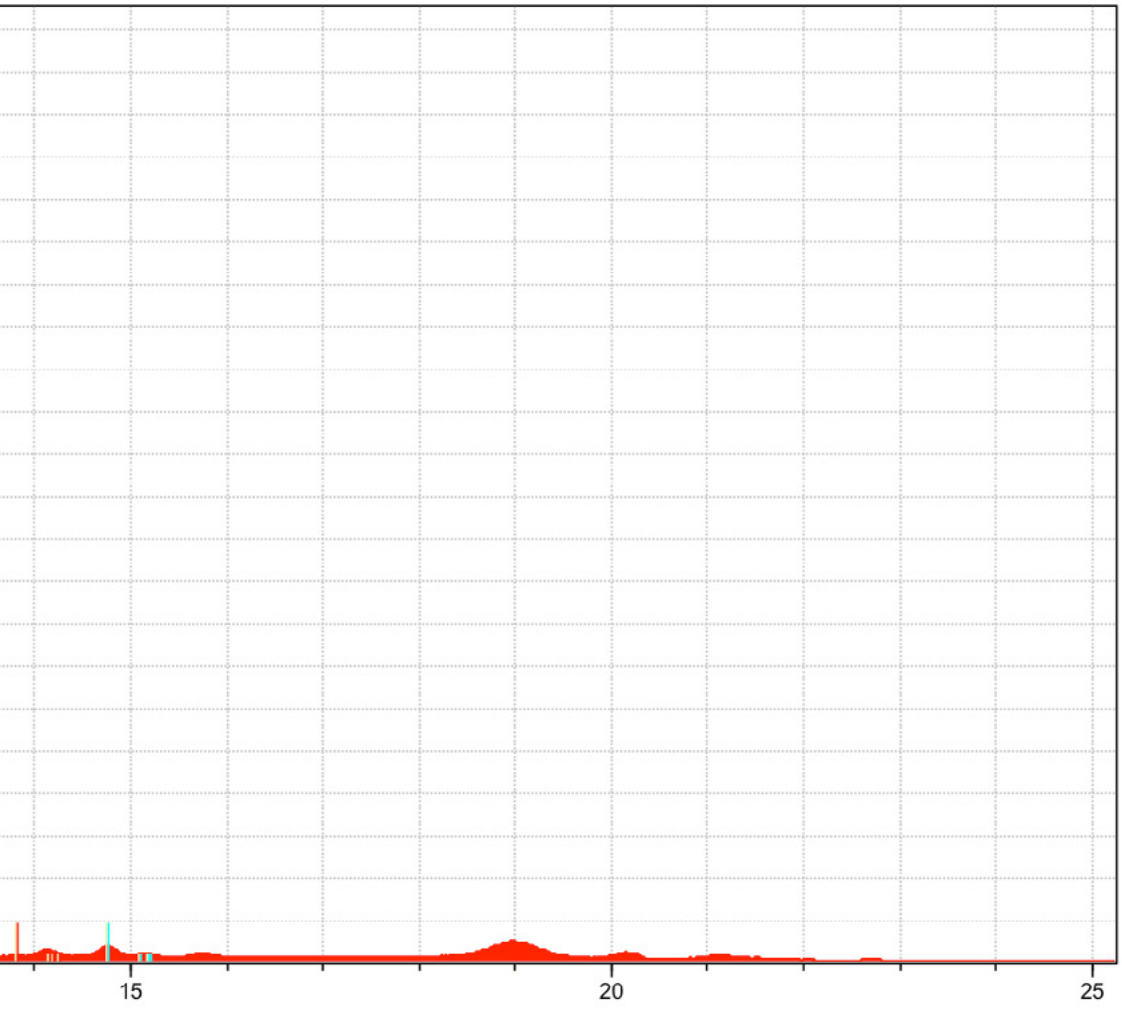
4.5 µA

vacuum

filter: no

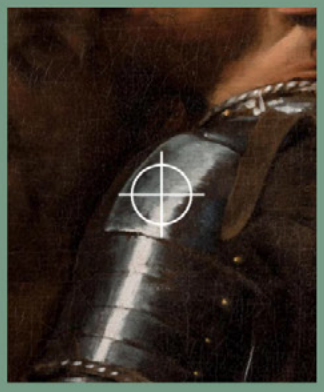
time: 120 seconds




15
20
25

Location 33

The soldier's armor highlight



Notes / possible pigments

Lead white; blue from copper-based pigment, possibly azurite; chalk; umber

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Calcium (Ca)	Manganese (Mn)
	Copper (Cu)	
	Iron (Fe)	

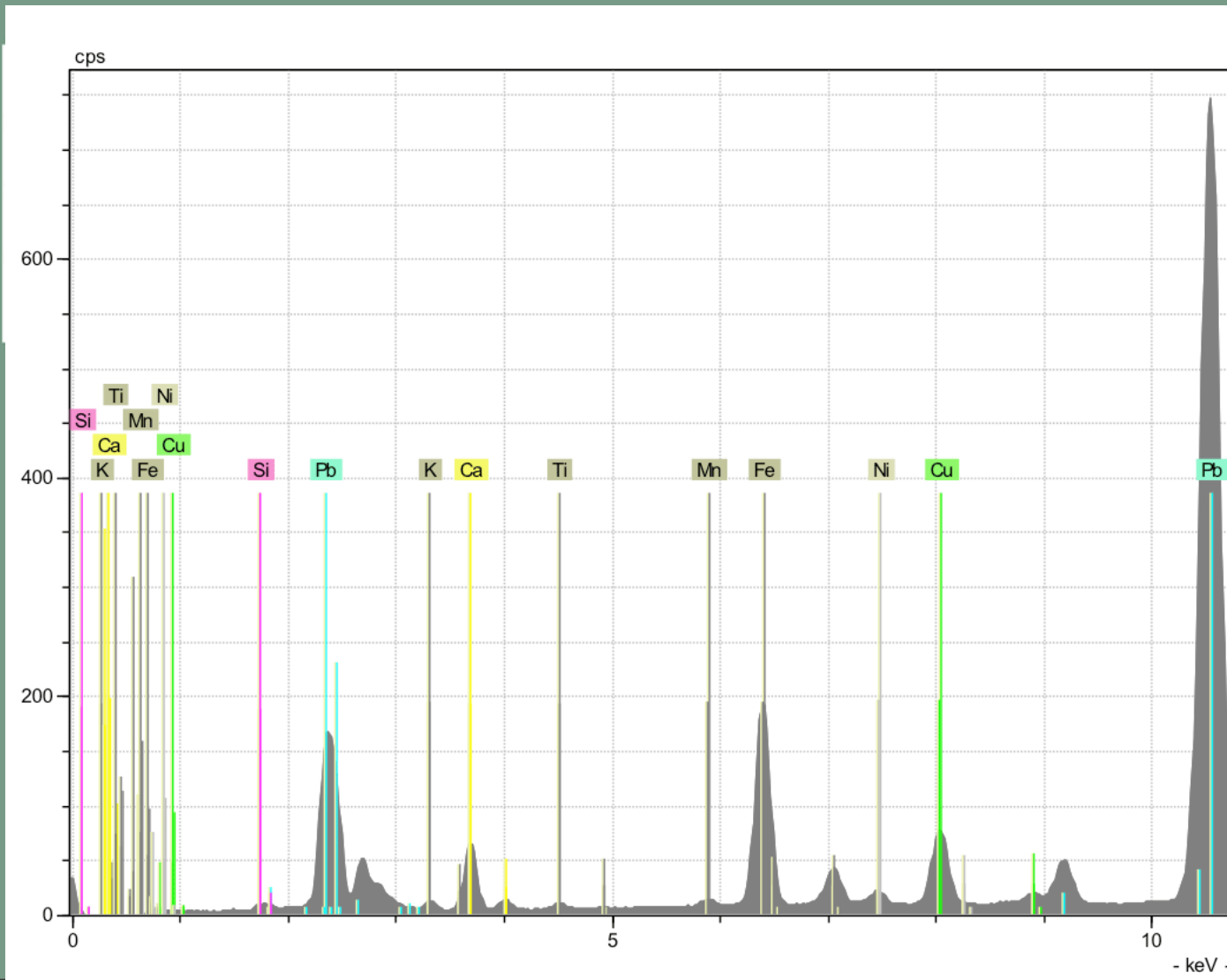
40 kV

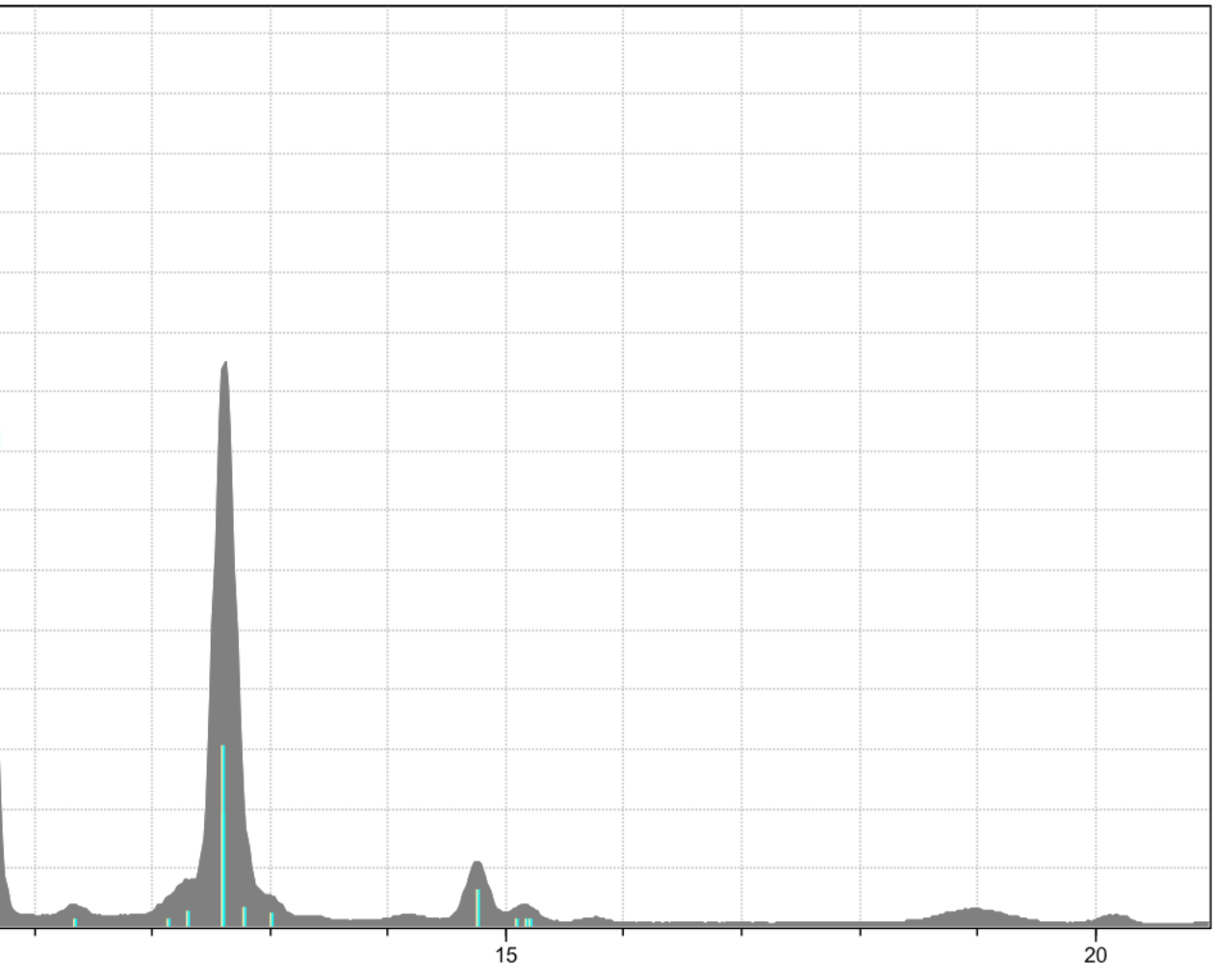
4.5 µA

vacuum

filter: no

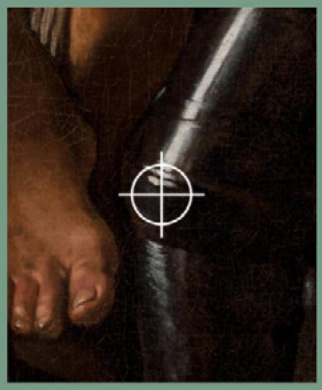
time: 120 seconds




15
20

Location 34

The soldier's black armor



Notes / possible pigments

Lead white; iron-based pigment; azurite; chalk; umber

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Manganese (Mn)
Lead (Pb)	Copper (Cu)	Phosphorus (P)
		Potassium (K)
		Silicon (Si)

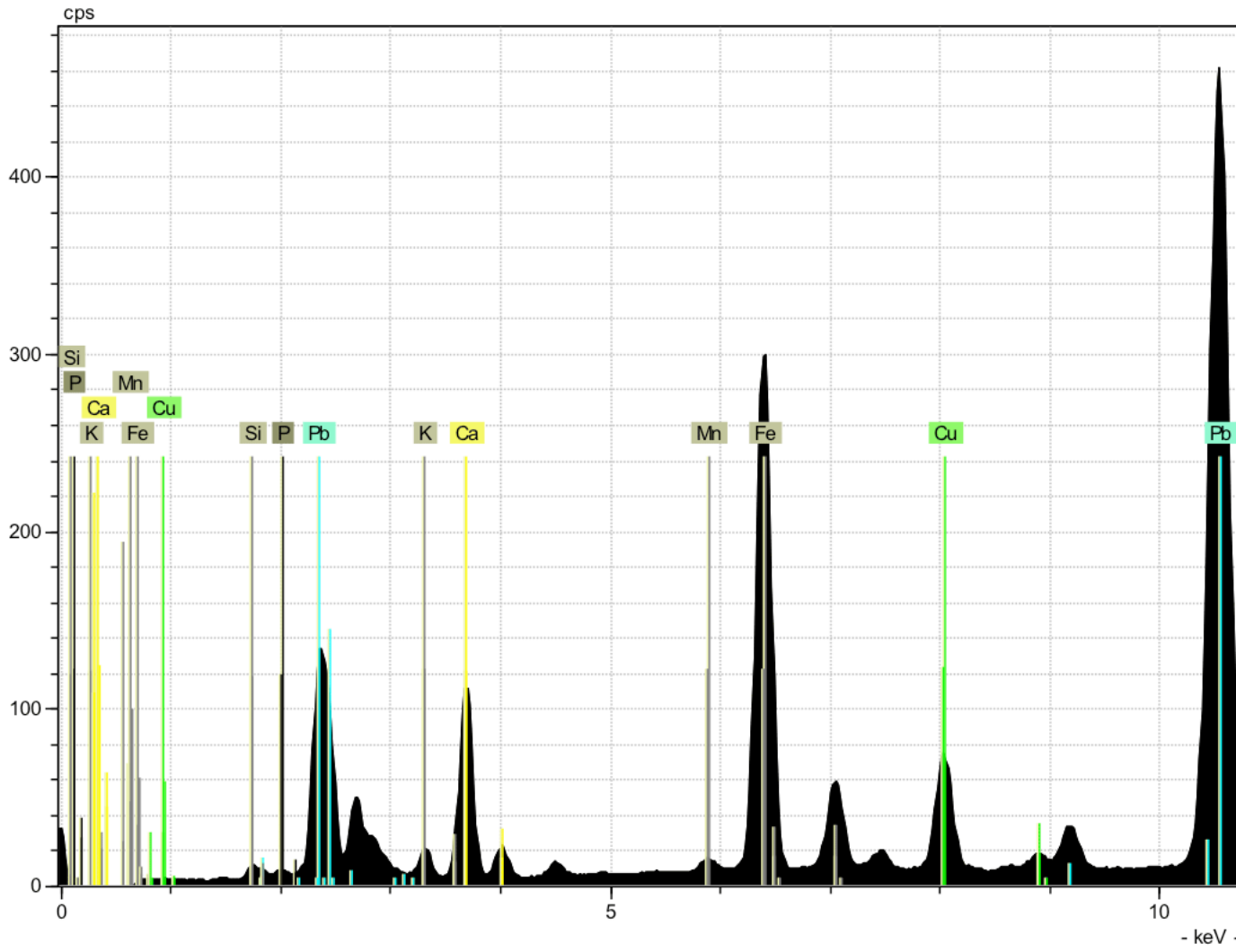
40 kV

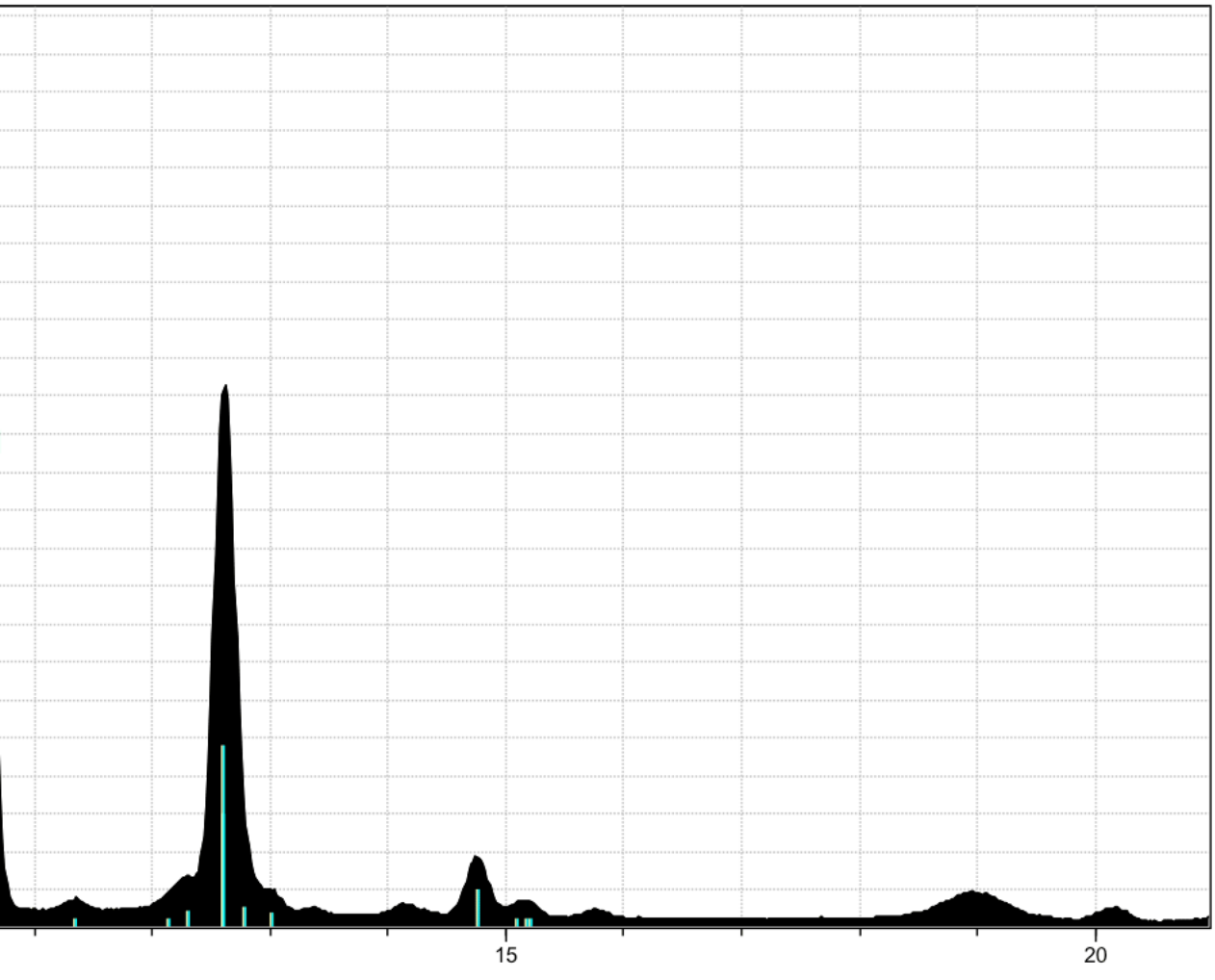
4.5 µA

vacuum

filter: no

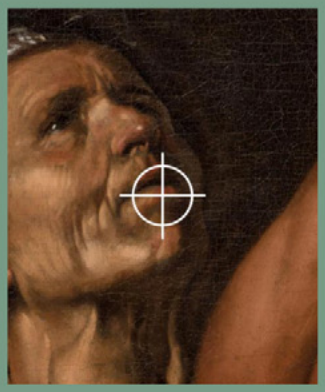
time: 120 seconds




15
20

Location 35

The old woman's lips

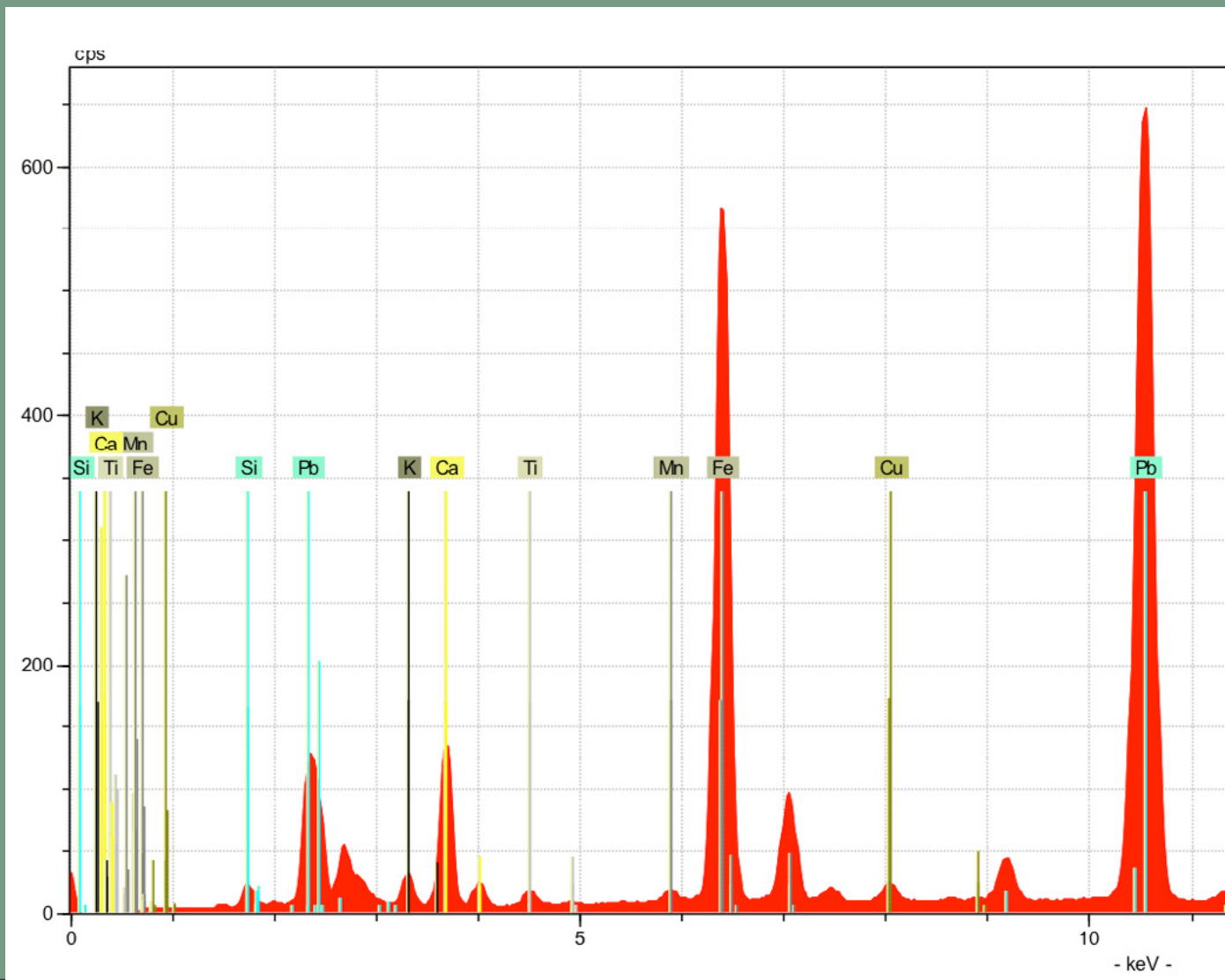


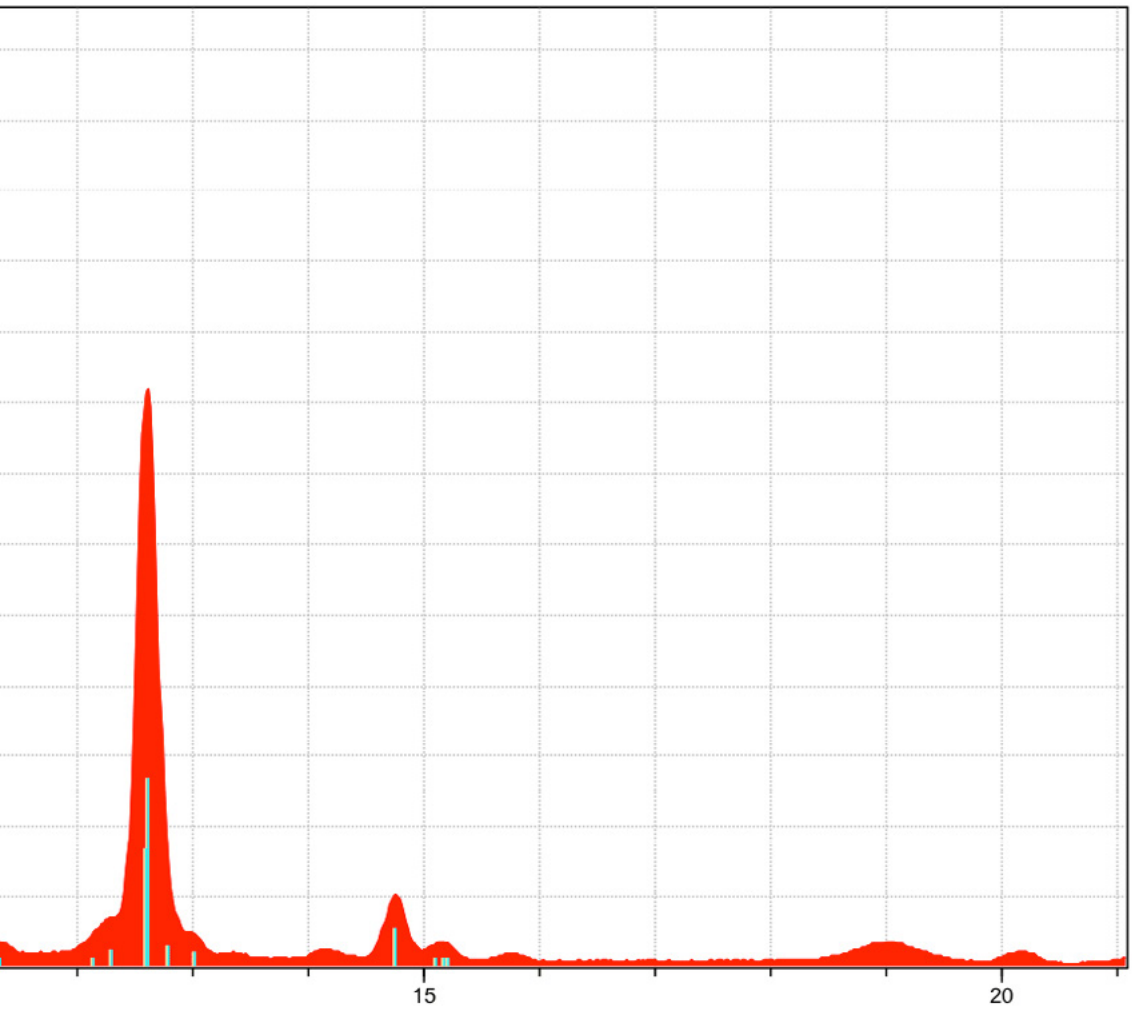
Notes / possible pigments

No trace of mercury in red lips, likely an iron-based pigment; lead white, likely from underlying *abbozzo*

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Copper (Cu)
Lead (Pb)		Manganese (Mn)
		Potassium (K)
		Silicon (Si)
		Titanium (Ti)

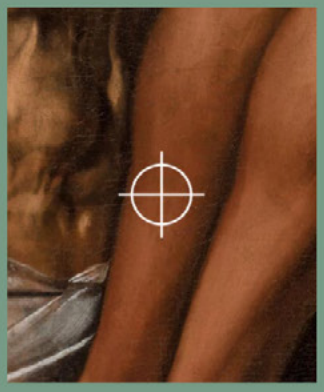
40 kV
4.5 µA
vacuum
filter: no
time: 120 seconds




15
20

Location 36

Left calf of the executioner on the ladder



Notes / possible pigments

Lead white; iron-based pigment; copper-based pigment, likely azurite

Major intensity	Trace intensity
Iron (Fe)	Calcium (Ca)
Lead (Pb)	Copper (Cu)
	Manganese (Mn)
	Potassium (K)
	Silicon (Si)

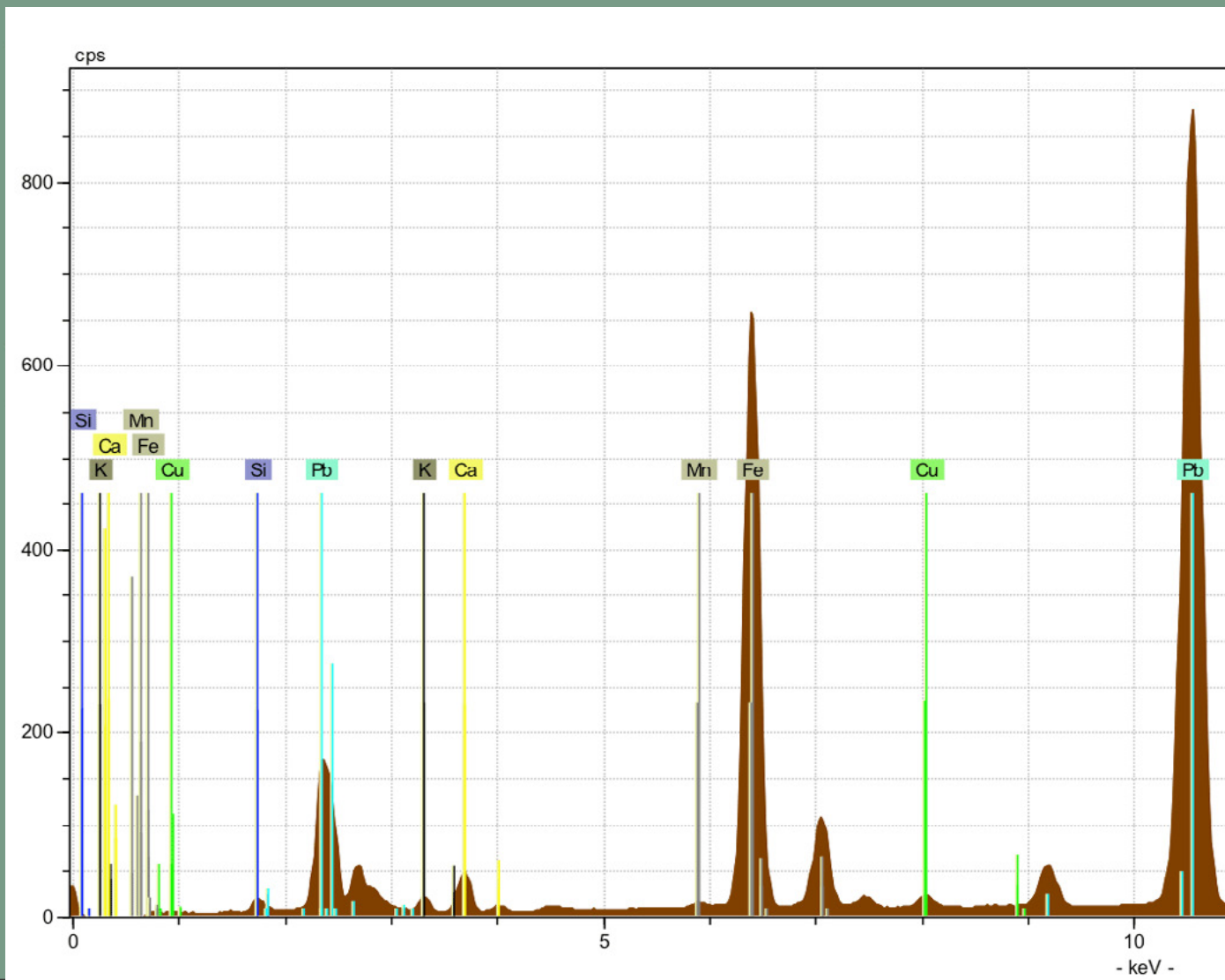
40 kV

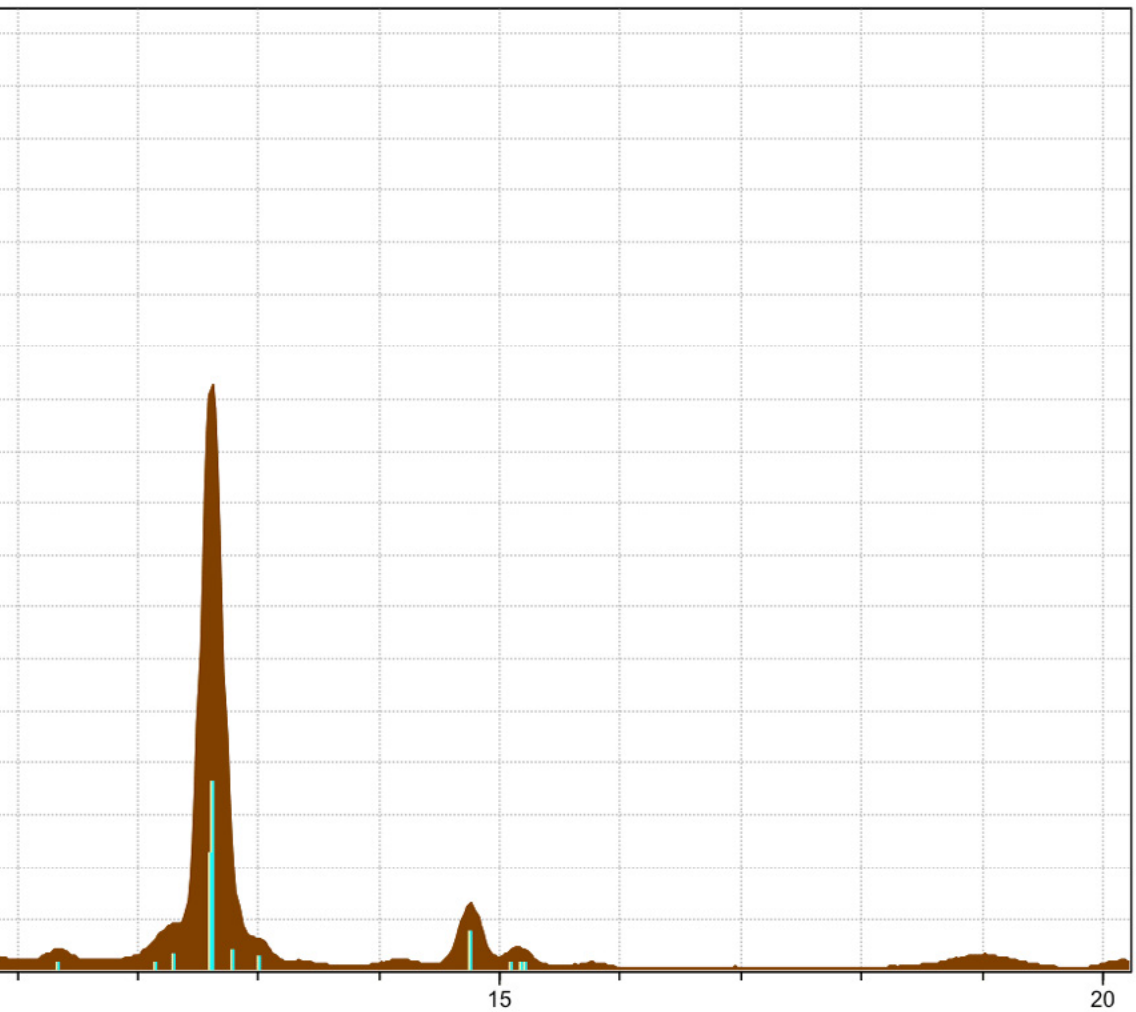
4.5 µA

vacuum

filter: no

time: 120 seconds




15
20

Location 38

Dark fold in red garment of the figure on the right

Notes / possible pigments

Lead white likely from underlying *abbozzo*; chalk; iron-based pigment; slight trace of mercury, possibly vermilion

Major intensity	Trace intensity
Calcium (Ca)	Copper (Cu)
Iron (Fe)	Manganese (Mn)
Lead (Pb)	Mercury (Hg)
	Potassium (K)
	Titanium (Ti)

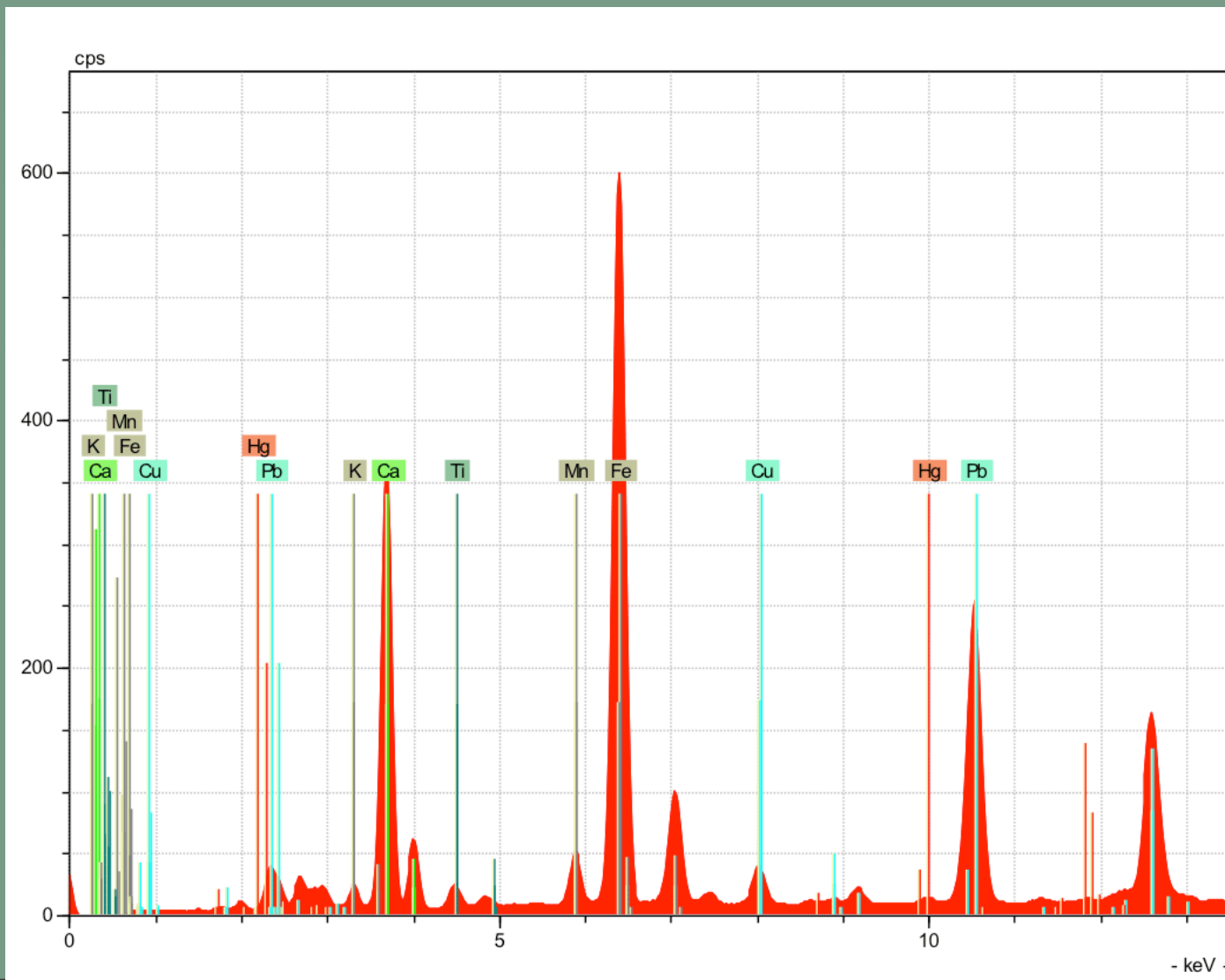
40 kV

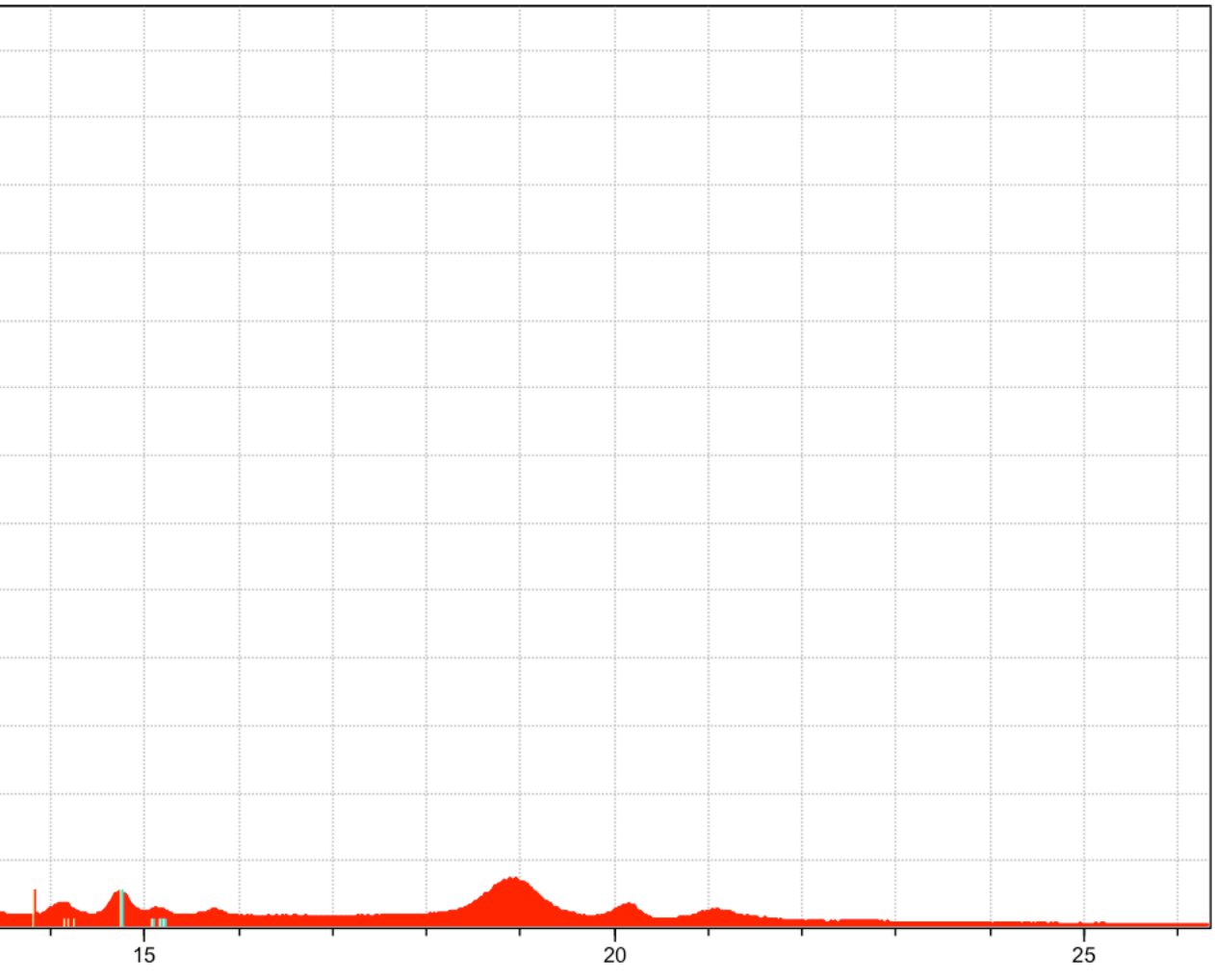
4.5 µA

vacuum

filter: no

time: 120 seconds




15
20
25

Location 39

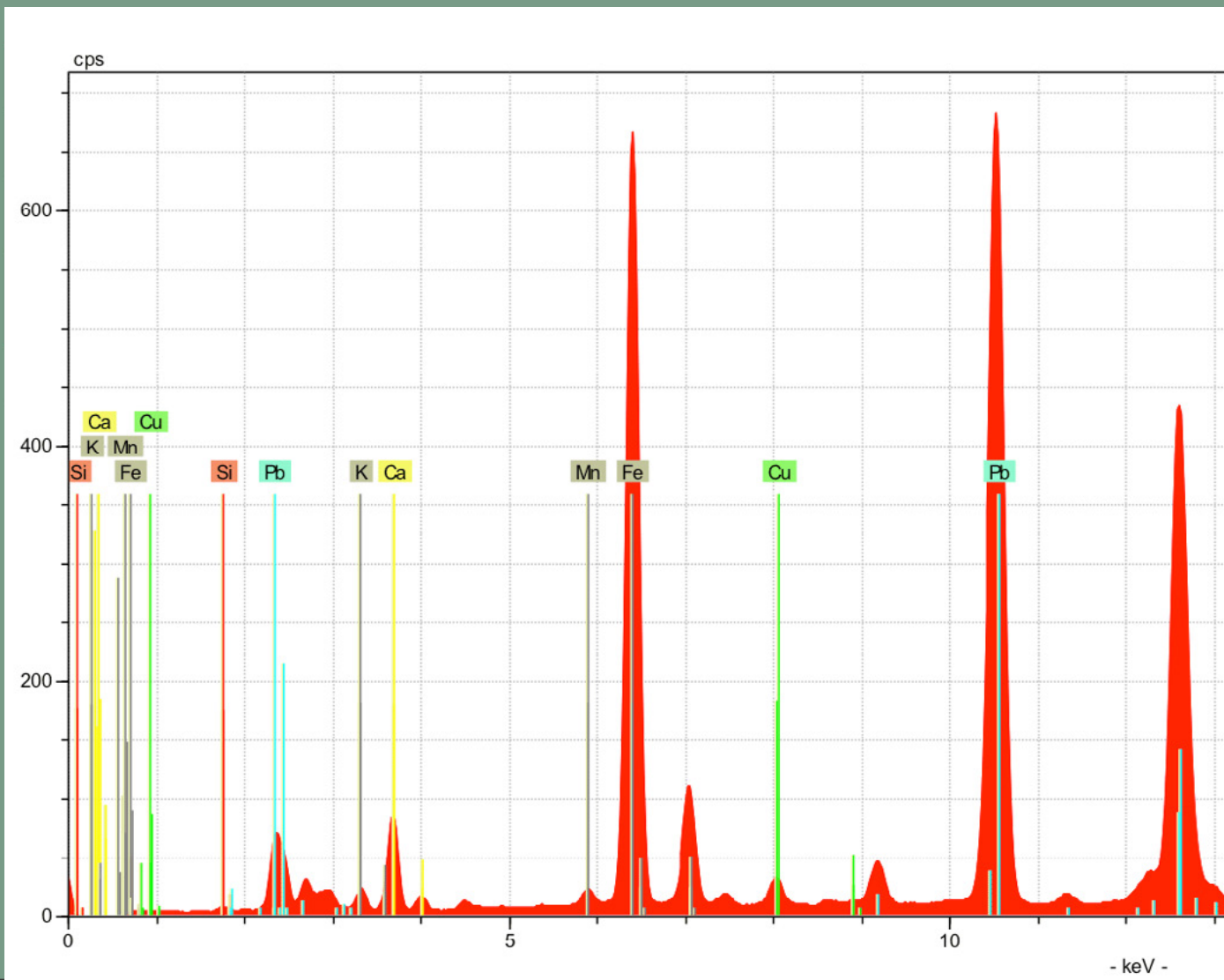
Red highlight fold in red garment of the figure on the right

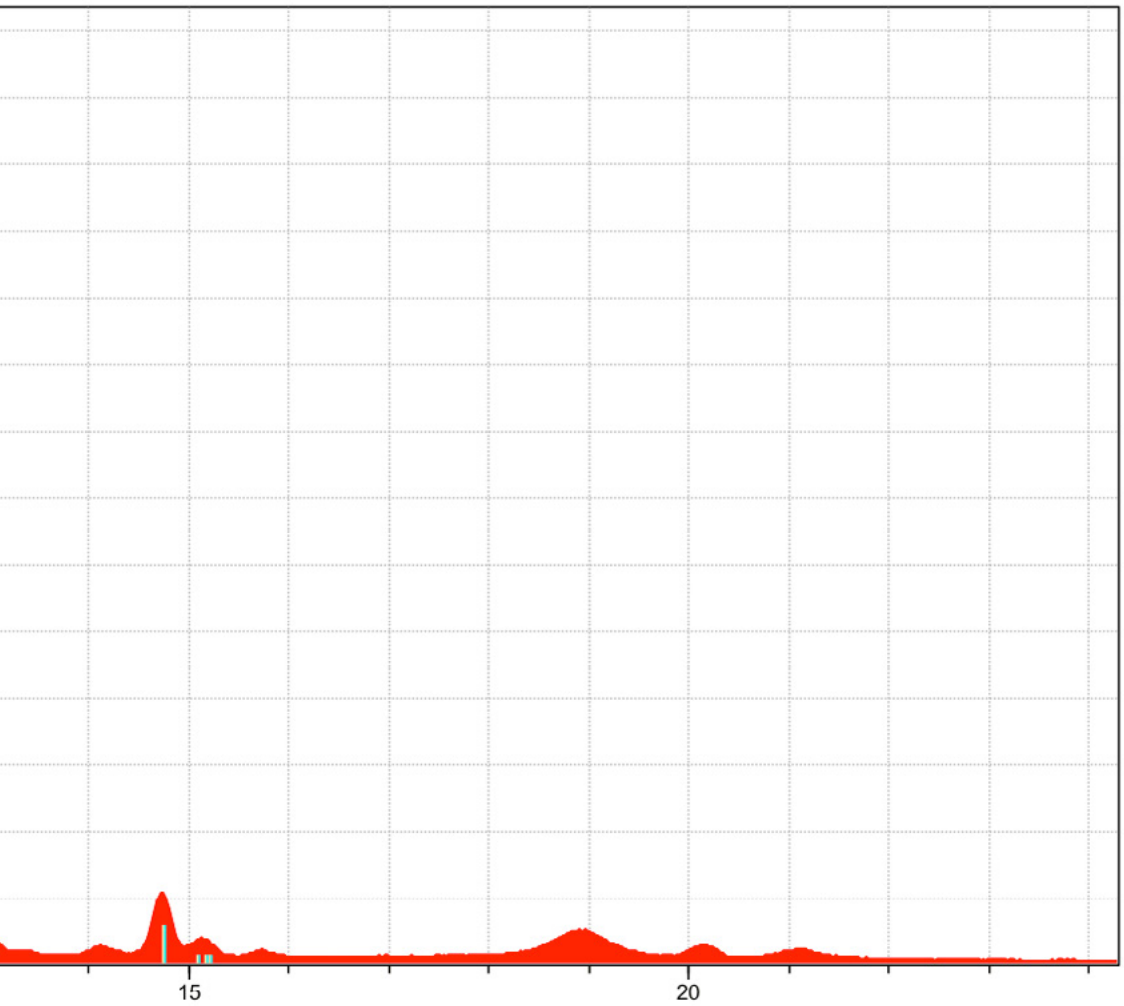
Notes / possible pigments

Vermilion not detected; red pigment
identified as hematite by Raman spectroscopy

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Copper (Cu)
Lead (Pb)		Manganese (Mn)
		Potassium (K)
		Silicon (Si)

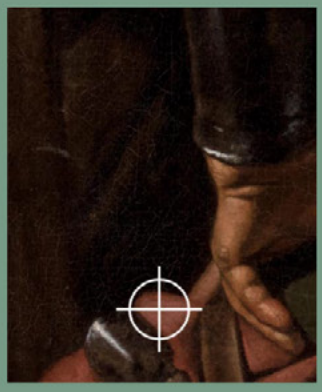
40 kV
4.5 µA
air
filter: no
time: 120 seconds




15
20

Location 41

The soldier's salmon-colored pants



Notes / possible pigments

Iron-based pigment; lead white; azurite, confirmed by Raman spectroscopy

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Manganese (Mn)
Lead (Pb)	Copper (Cu)	
	Mercury (Hg)	

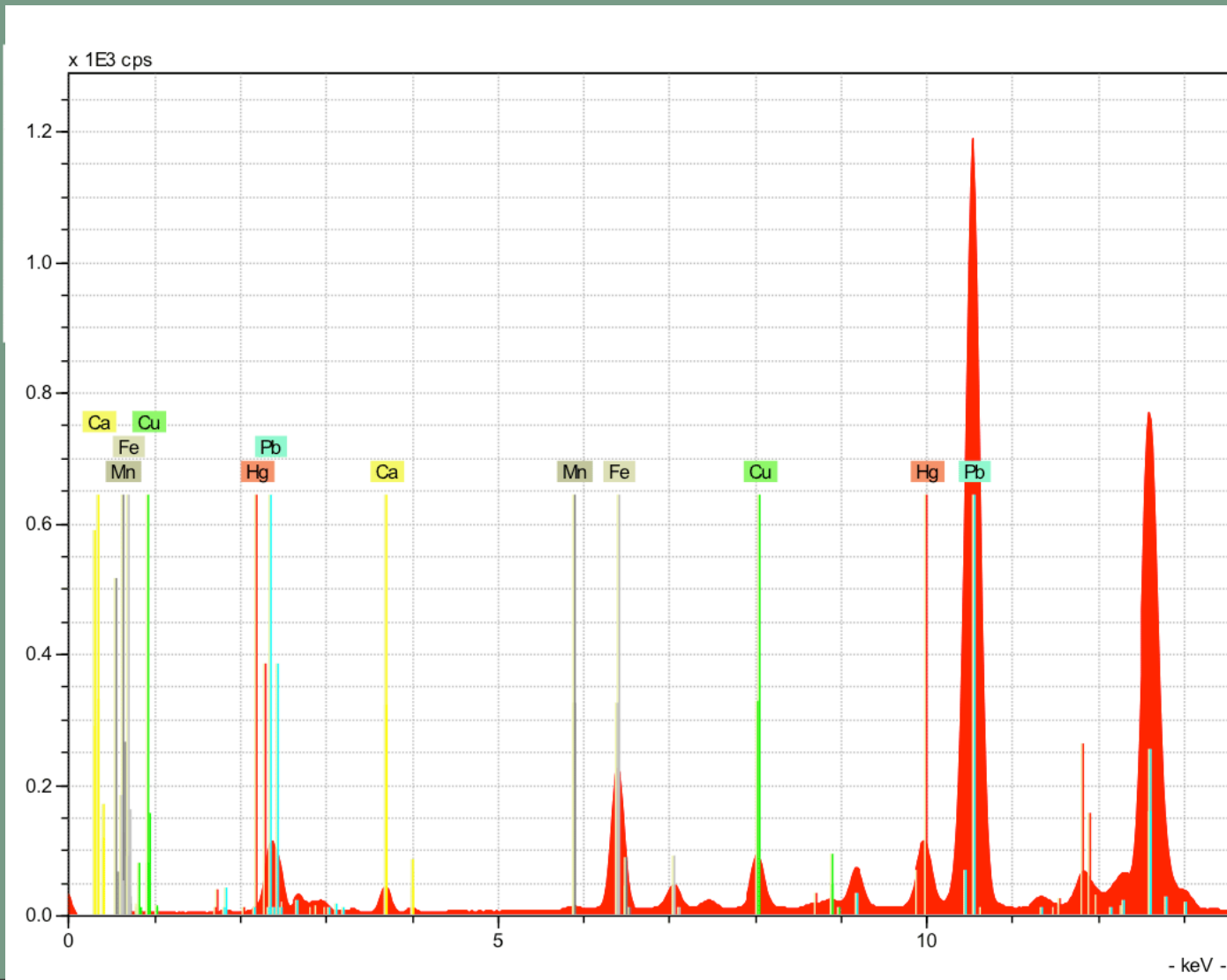
40 kV

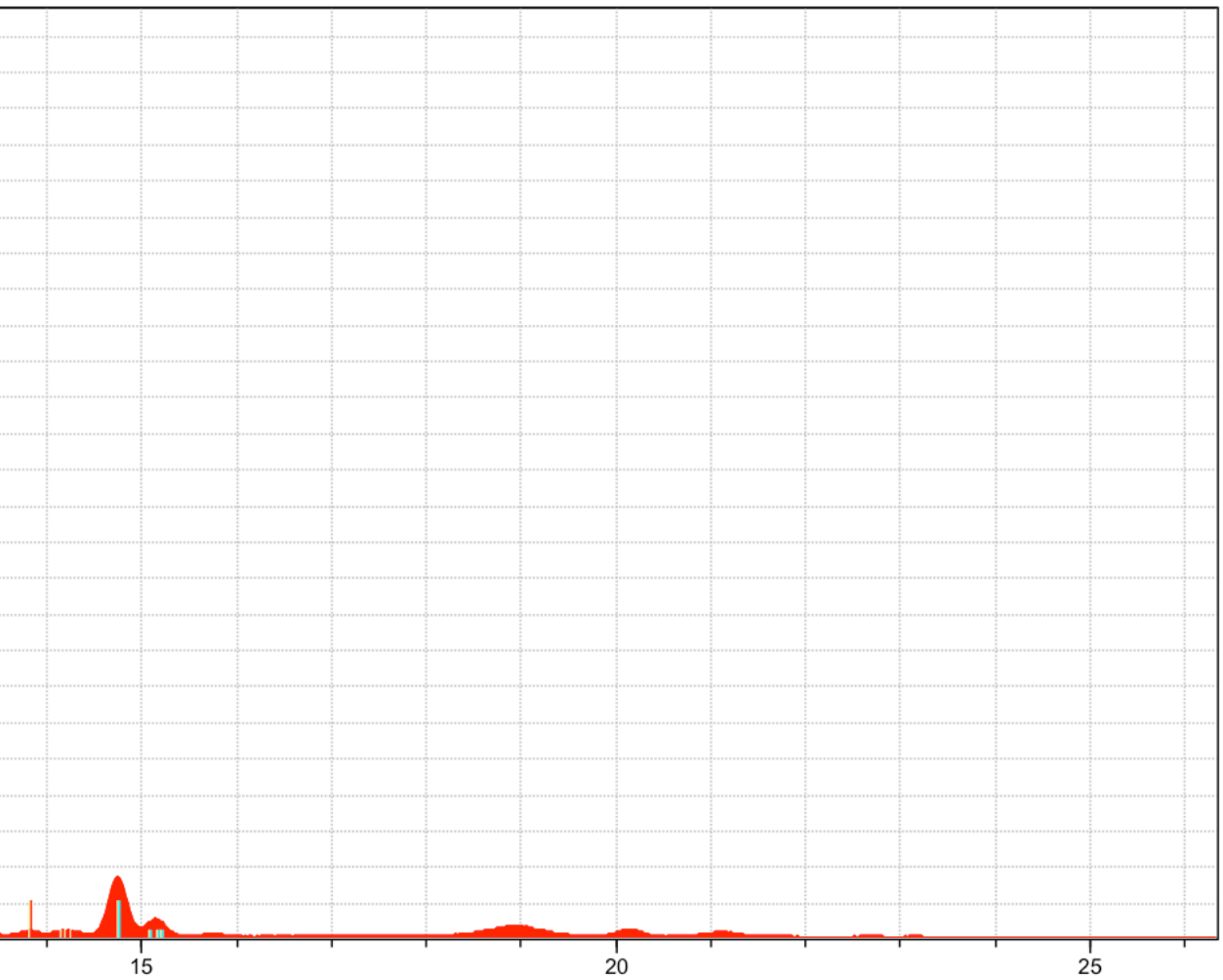
4.5 µA

air

filter: no

time: 120 seconds




15
20
25

Location 42

Pinkie finger of the soldier's left hand

Notes / possible pigments

Lead white; trace of copper likely due to underlying malachite in green waistcoat

Major intensity	Minor intensity	Trace intensity
Lead (Pb)	Iron (Fe)	Calcium (Ca)
		Copper (Cu)

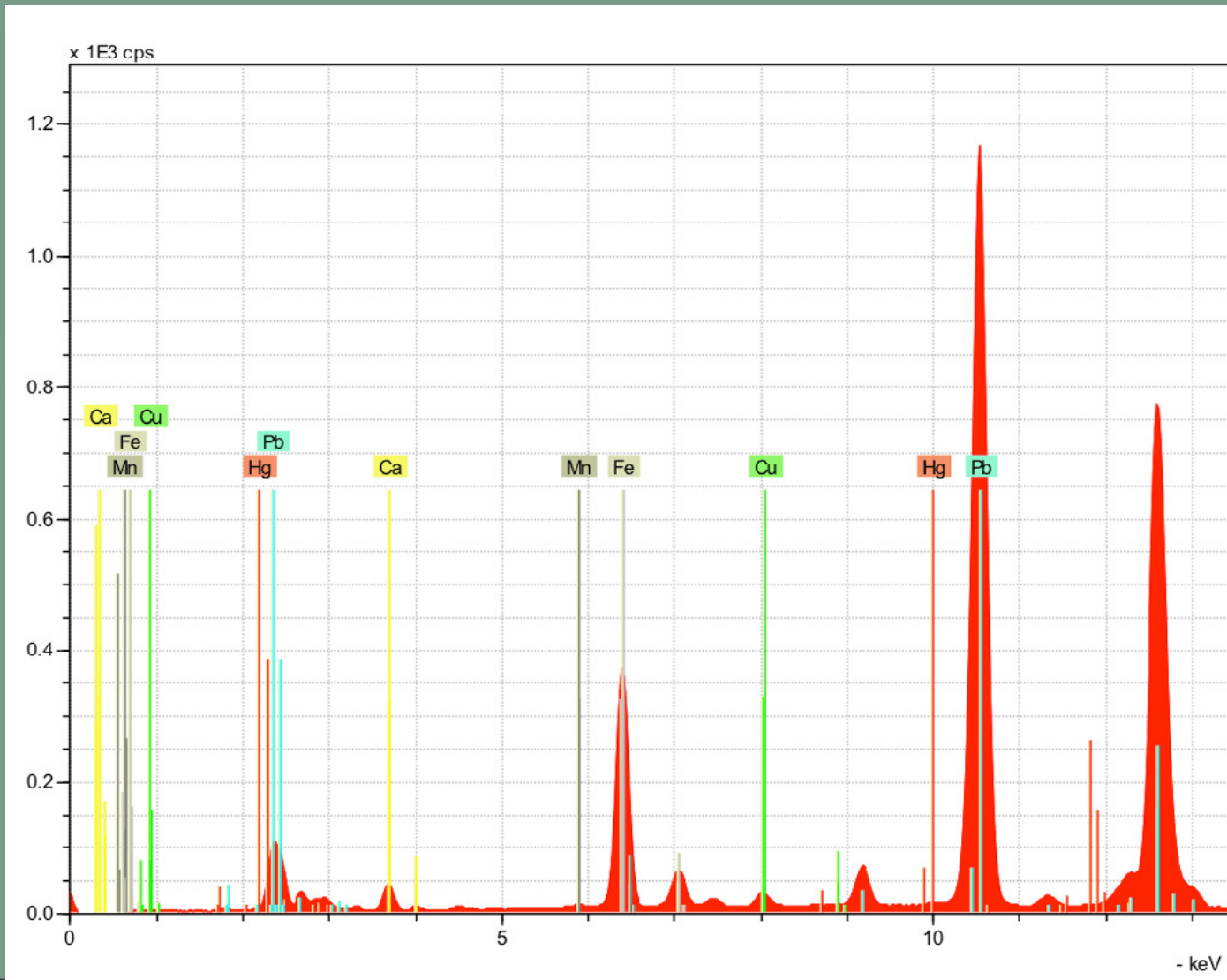
40 kV

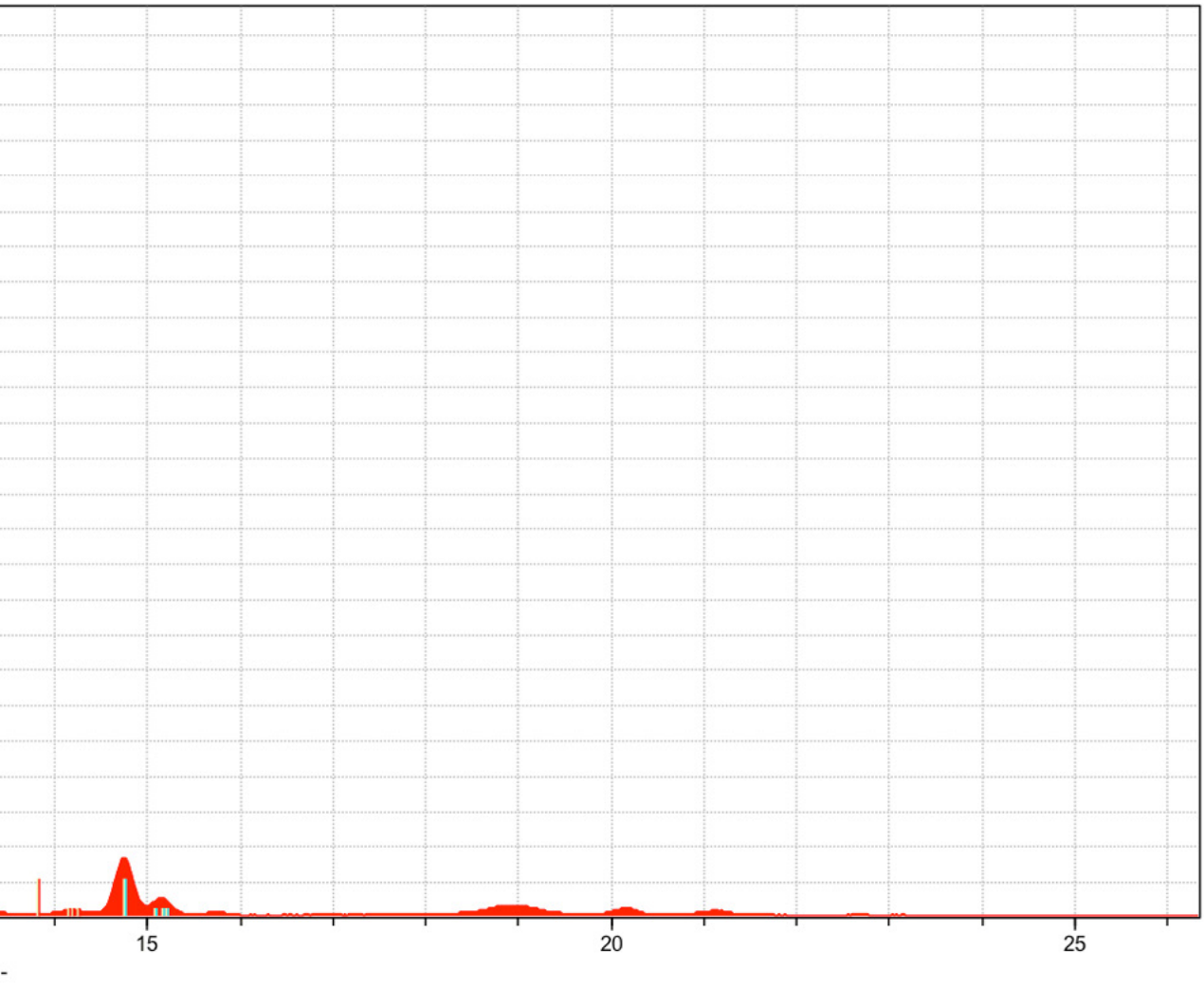
4.5 µA

air

filter: no

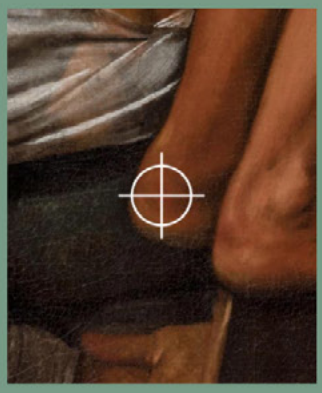
time: 120 seconds




15
20
25

Location 43

Heel of the executioner standing on the ladder



Notes / possible pigments

Lead white; iron-based pigment; possible underlying azurite; umber; chalk

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Manganese (Mn)
Lead (Pb)	Copper (Cu)	

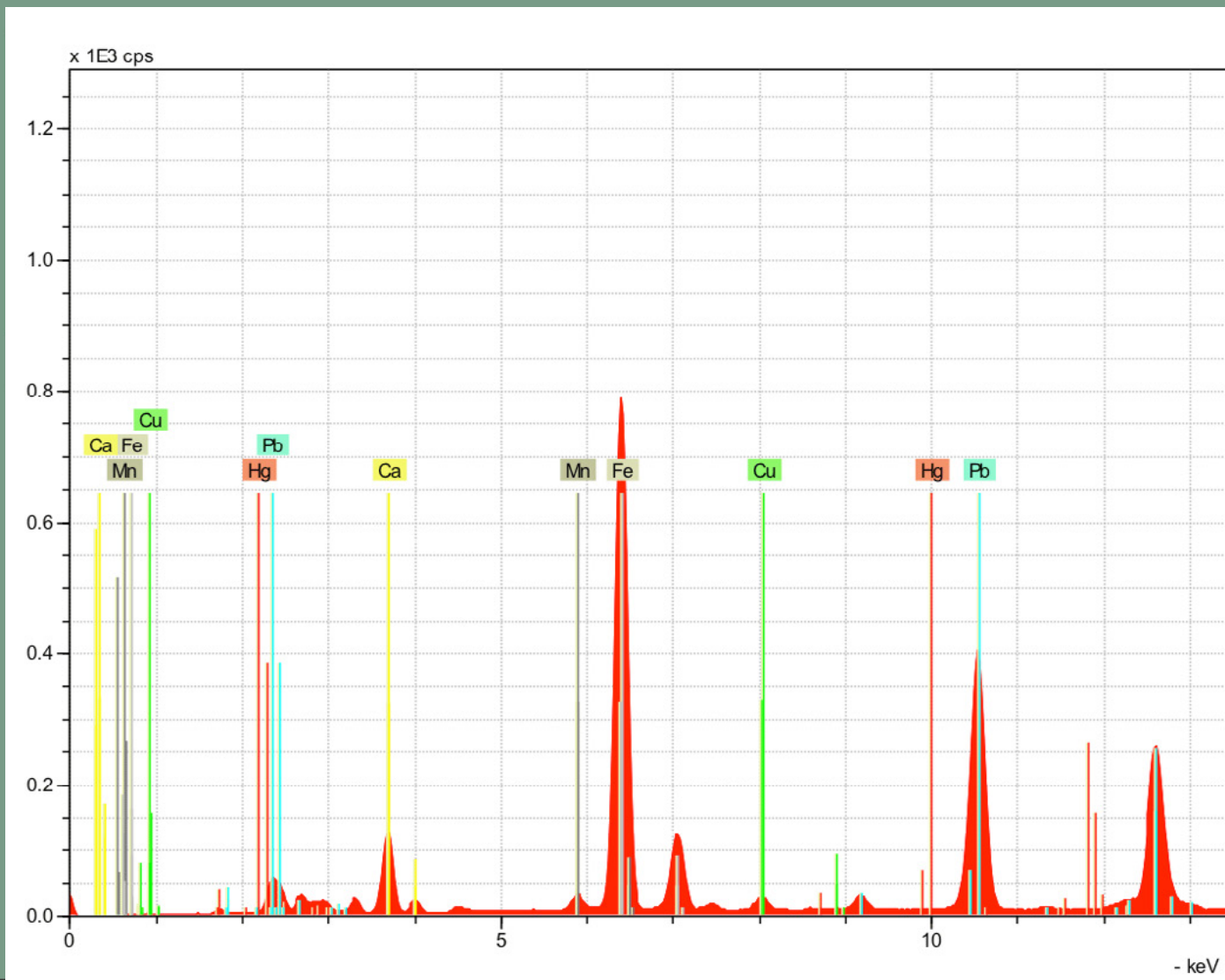
40 kV

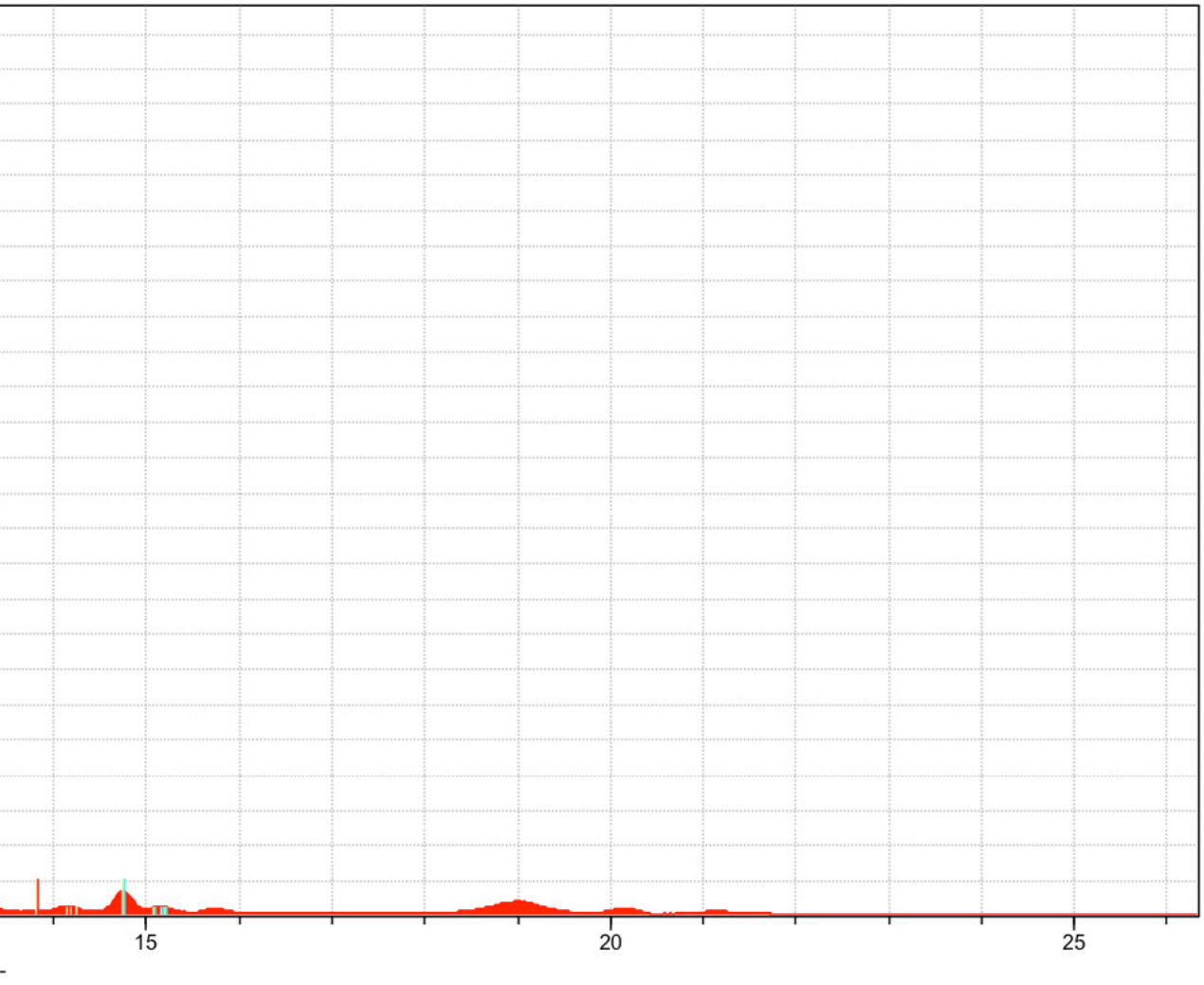
4.5 µA

air

filter: no

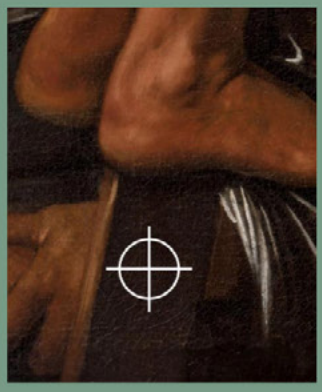
time: 120 seconds




15
20
25

Location 44

Ladder under the executioner's foot



Notes / possible pigments

Iron-based pigment; lead white; umber; chalk; copper-based pigment

Major intensity	Minor intensity
Calcium (Ca)	Copper (Cu)
Iron (Fe)	Manganese (Mn)
Lead (Pb)	

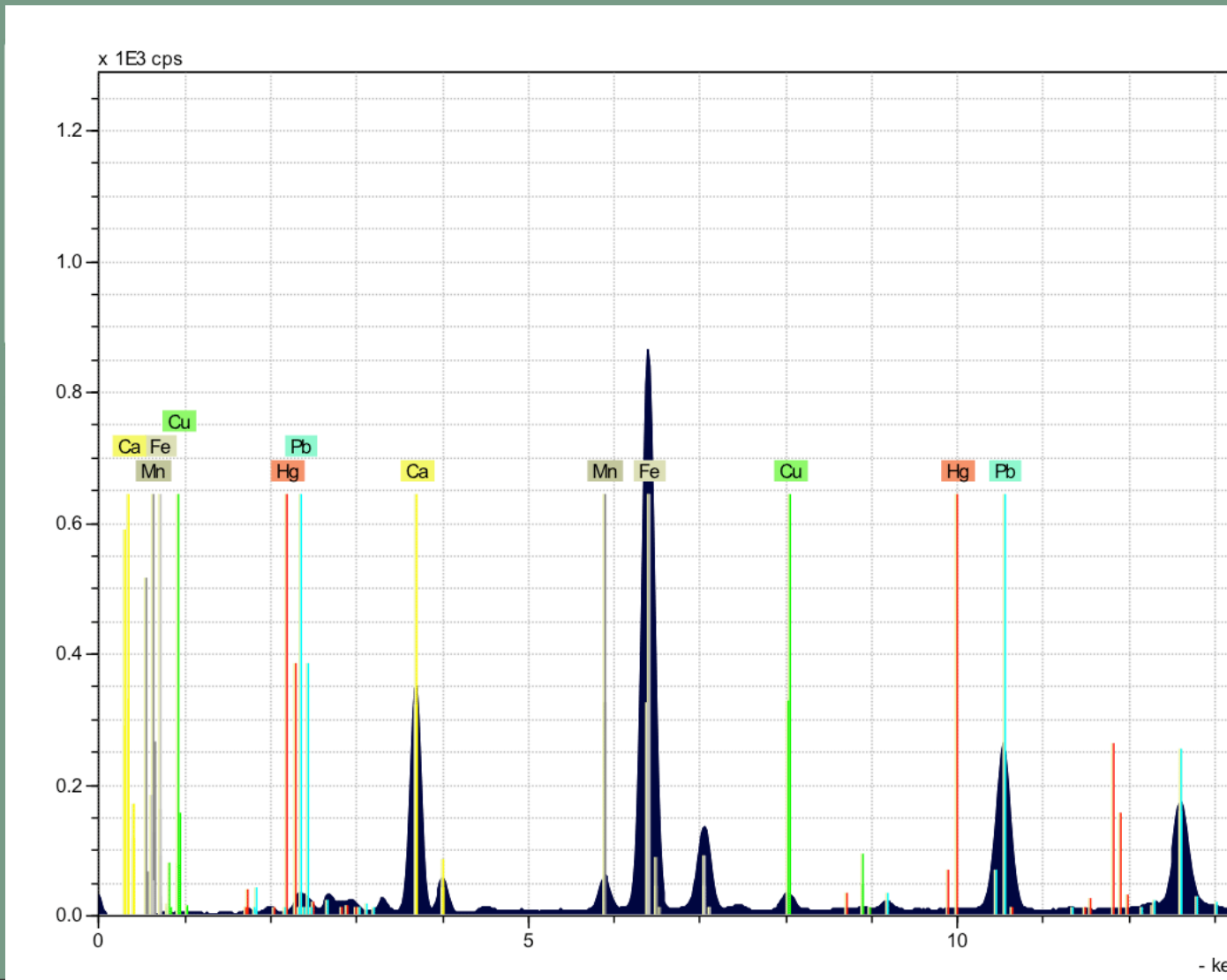
15 kV

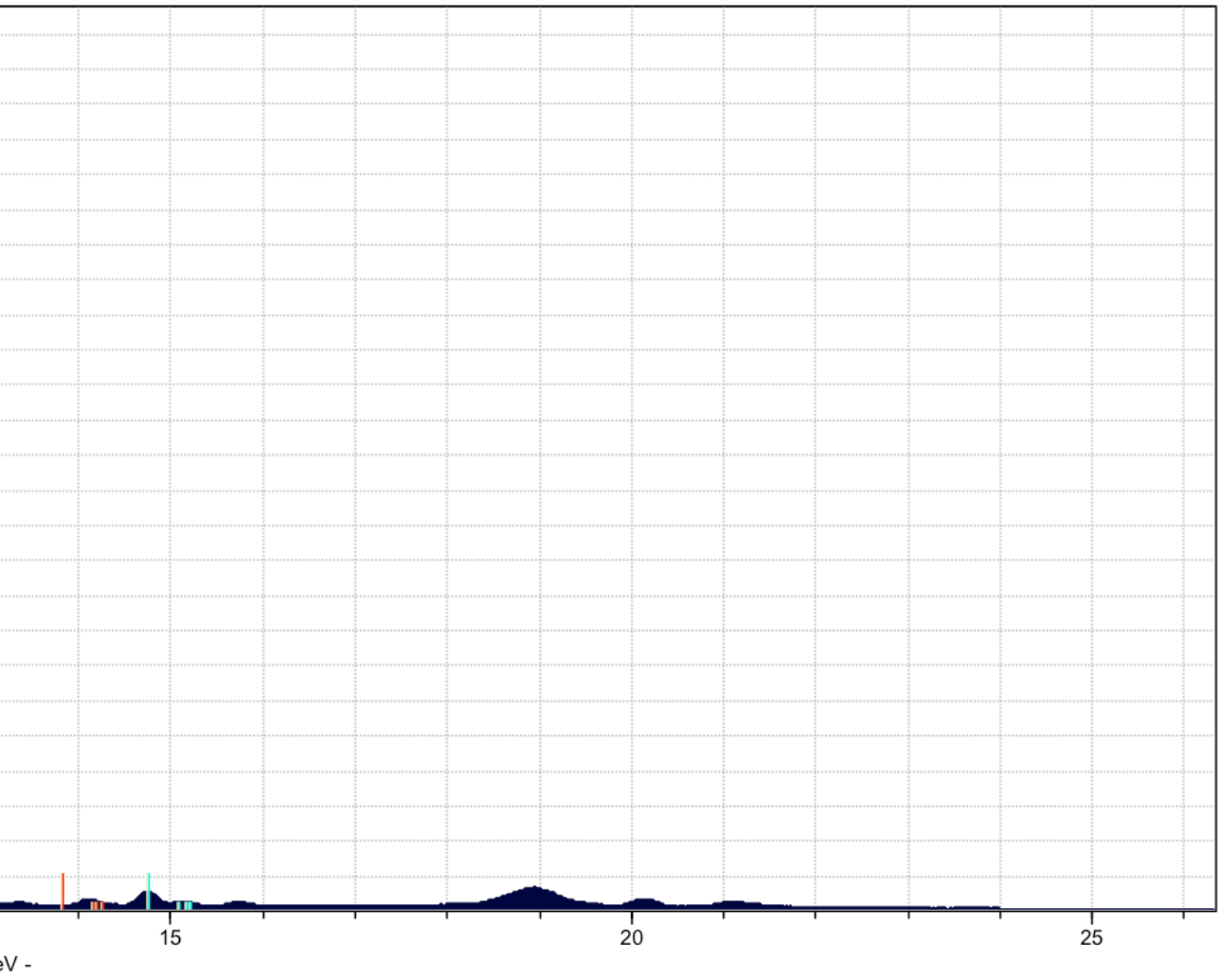
20 µA

air

filter: no

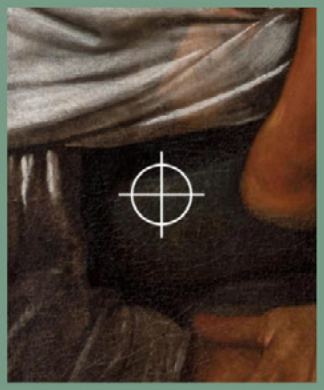
time: 120 seconds




15
20
25
eV -

Location 45

The old woman's blouse



Notes / possible pigments

Copper-based pigment, confirmed as azurite by Raman spectroscopy; iron-based pigment; chalk

Major intensity	Minor intensity	Trace intensity
Copper (Cu)	Calcium (Ca)	Potassium (K)
	Iron (Fe)	Manganese (Mn)

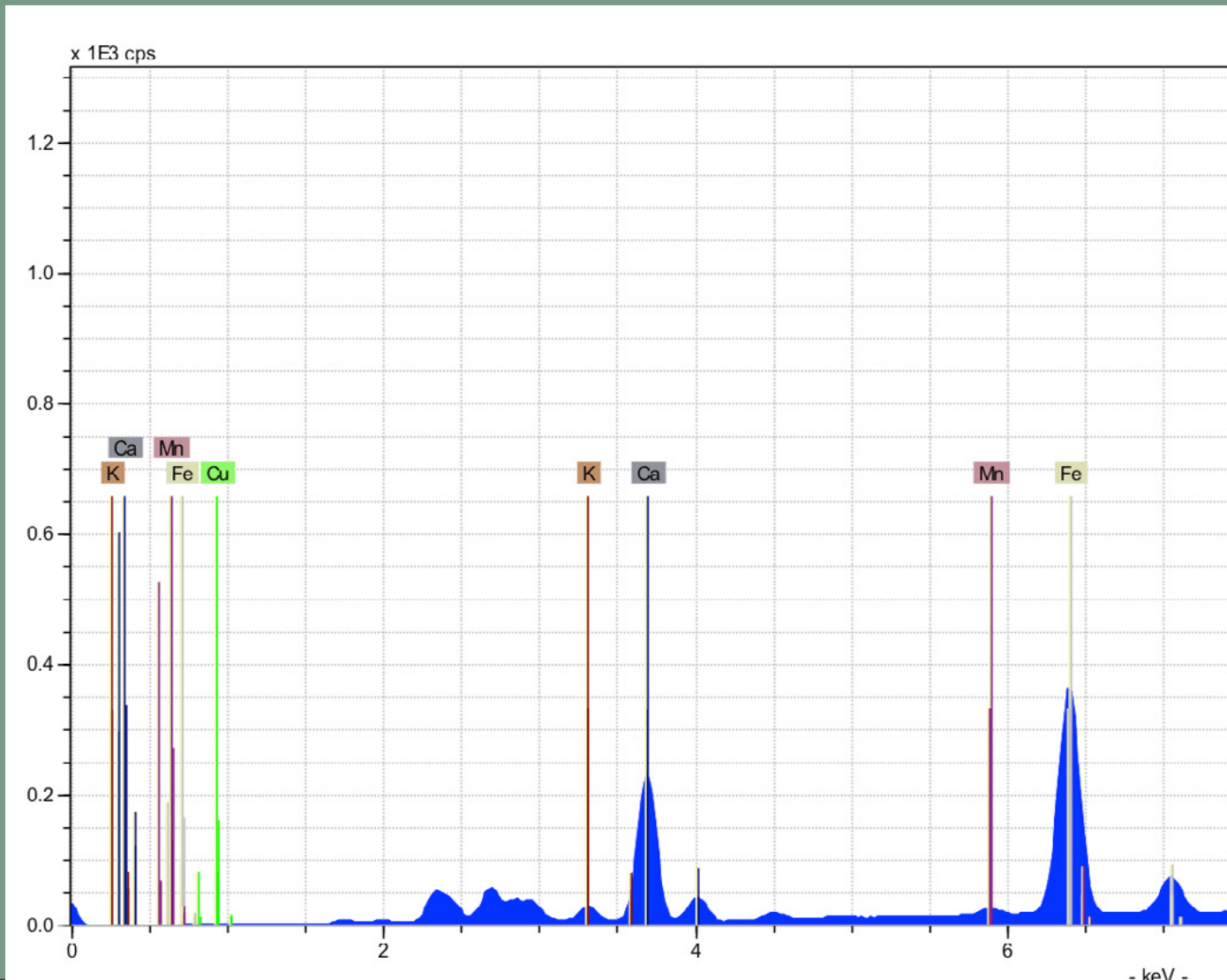
15 kV

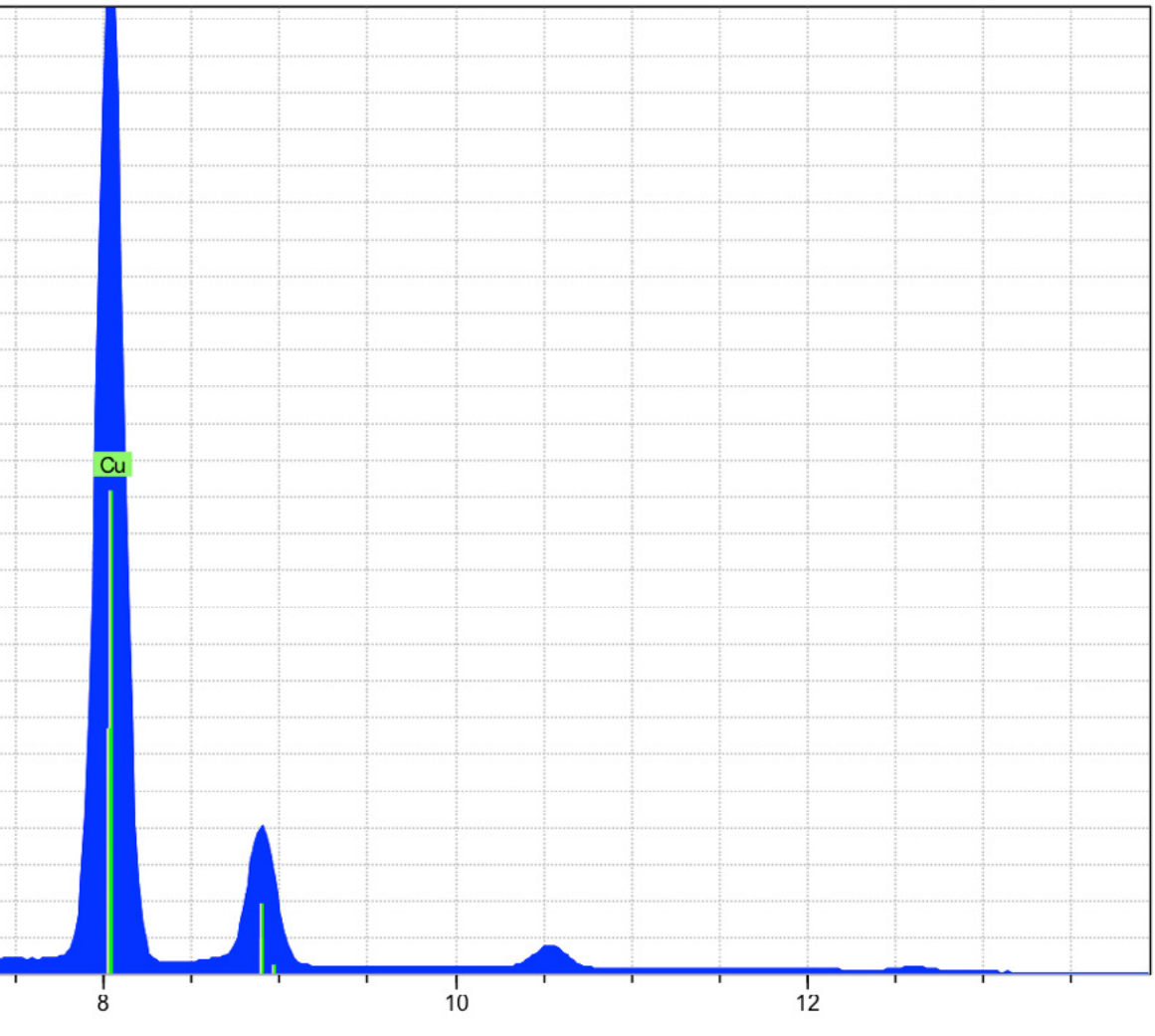
20 µA

air

filter: no

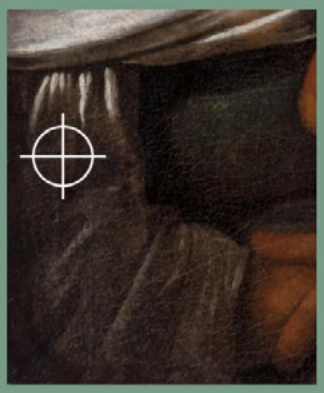
time: 120 seconds




Cu
8
10
12

Location 46

Right sleeve of the old woman's blouse



Notes / possible pigments

Lead white; iron-based pigment; umber; chalk; copper based-pigment, likely azurite

Major intensity	Minor intensity	Trace intensity
Iron (Fe)	Calcium (Ca)	Manganese (Mn)
Lead (Pb)	Copper (Cu	Potassium (K)
		Silicon (Si)
		Titanium (Ti)

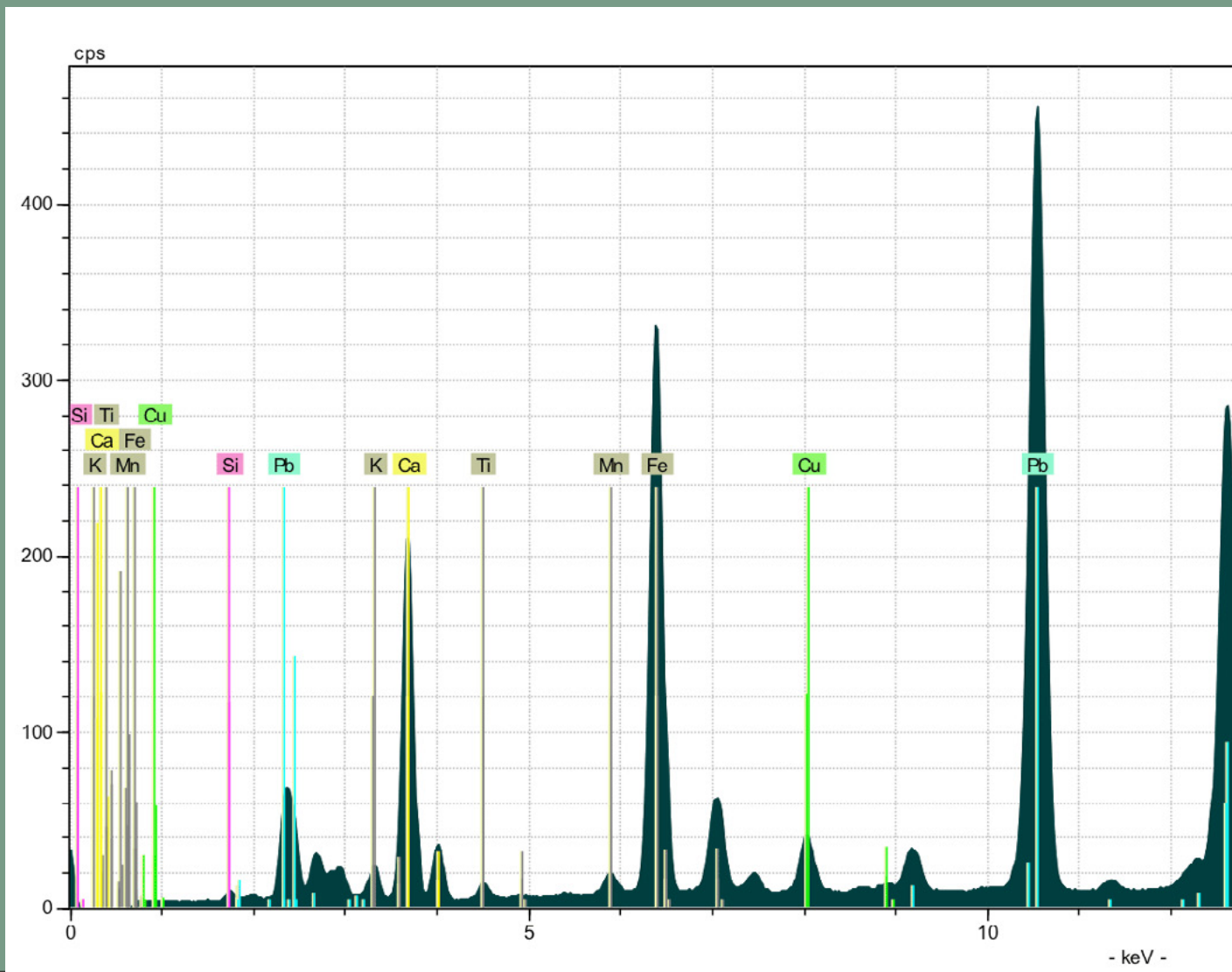
15 kV

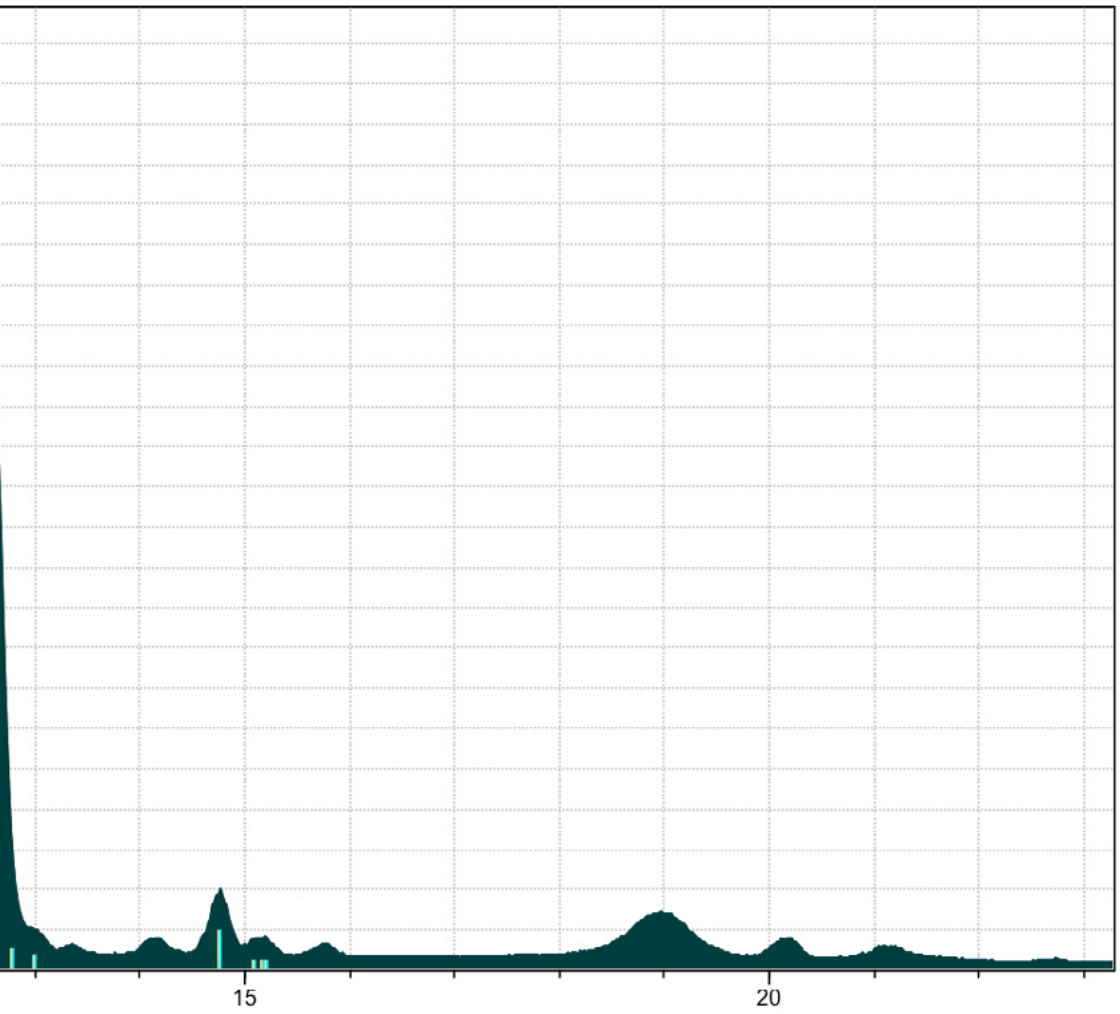
20 µA

air

filter: no

time: 120 seconds




15
20

Location 47a

Shadow area of the open-mouthed figure in the background

Notes / possible pigments

Iron-based pigment; copper-based pigment,
likely used to augment the dark drapery; chalk; umber

Major intensity	Minor intensity	Trace intensity
Copper (Cu)	Calcium (Ca)	Manganese (Mn)
Iron (Fe)		
Lead (Pb)		

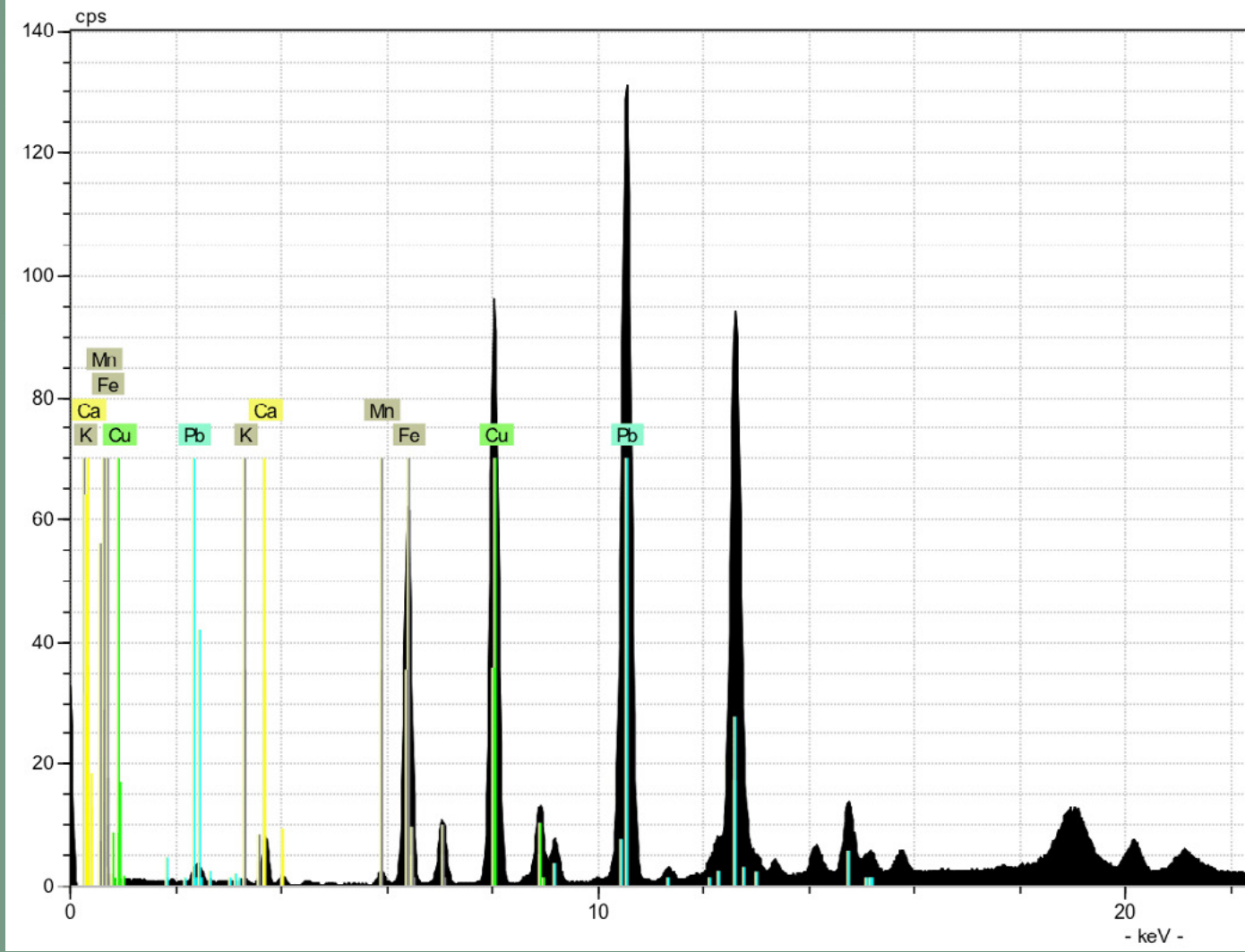
15 kV

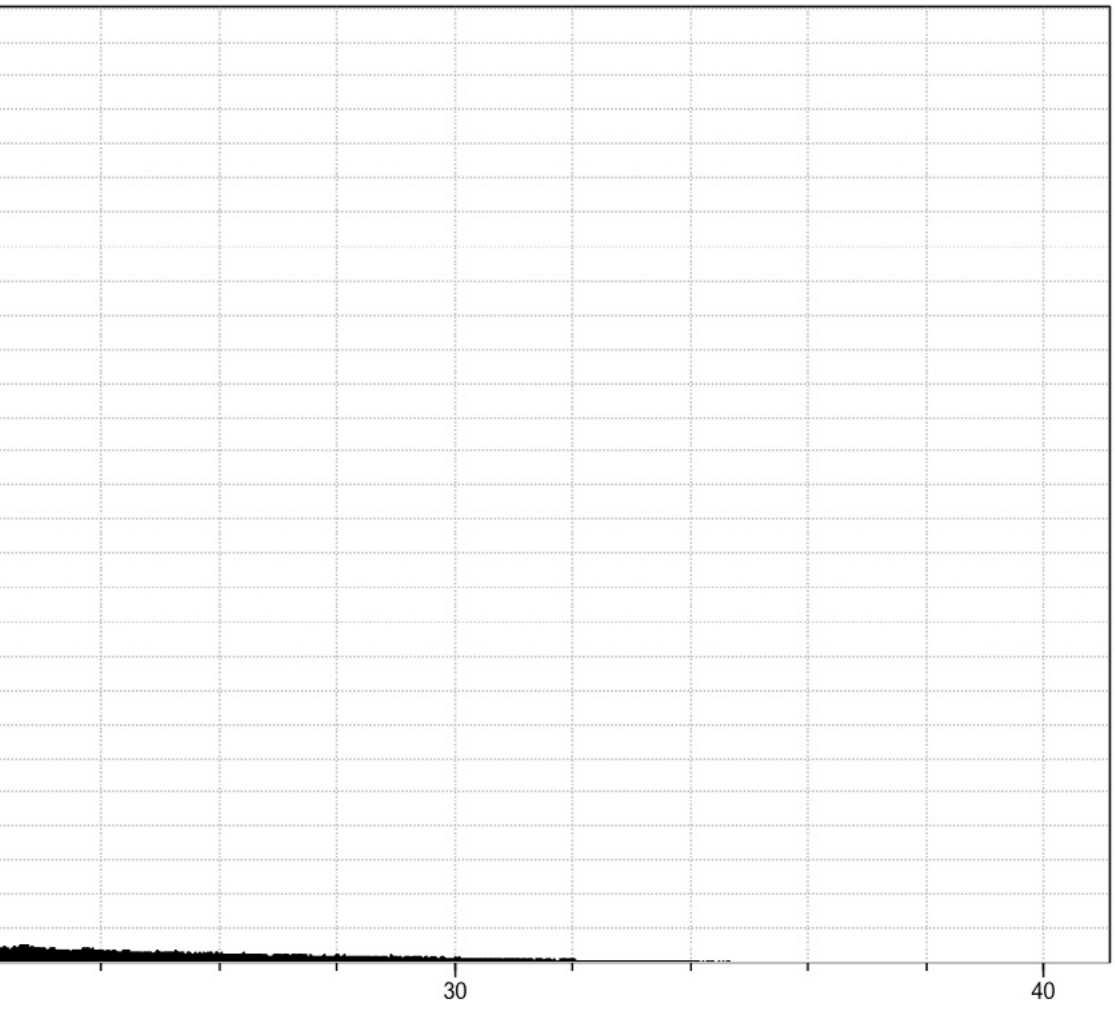
20 µA

air

filter: no

time: 120 seconds




30
40

Location 47b

Shadow area in the background figure's garment

Notes / possible pigments

Lead white; copper-based pigment; iron-based pigment; lead white; chalk; umber

Major intensity	Minor intensity	Trace intensity
Copper (Cu)	Calcium (Ca)	Manganese (Mn)
Iron (Fe)		
Lead (Pb)		

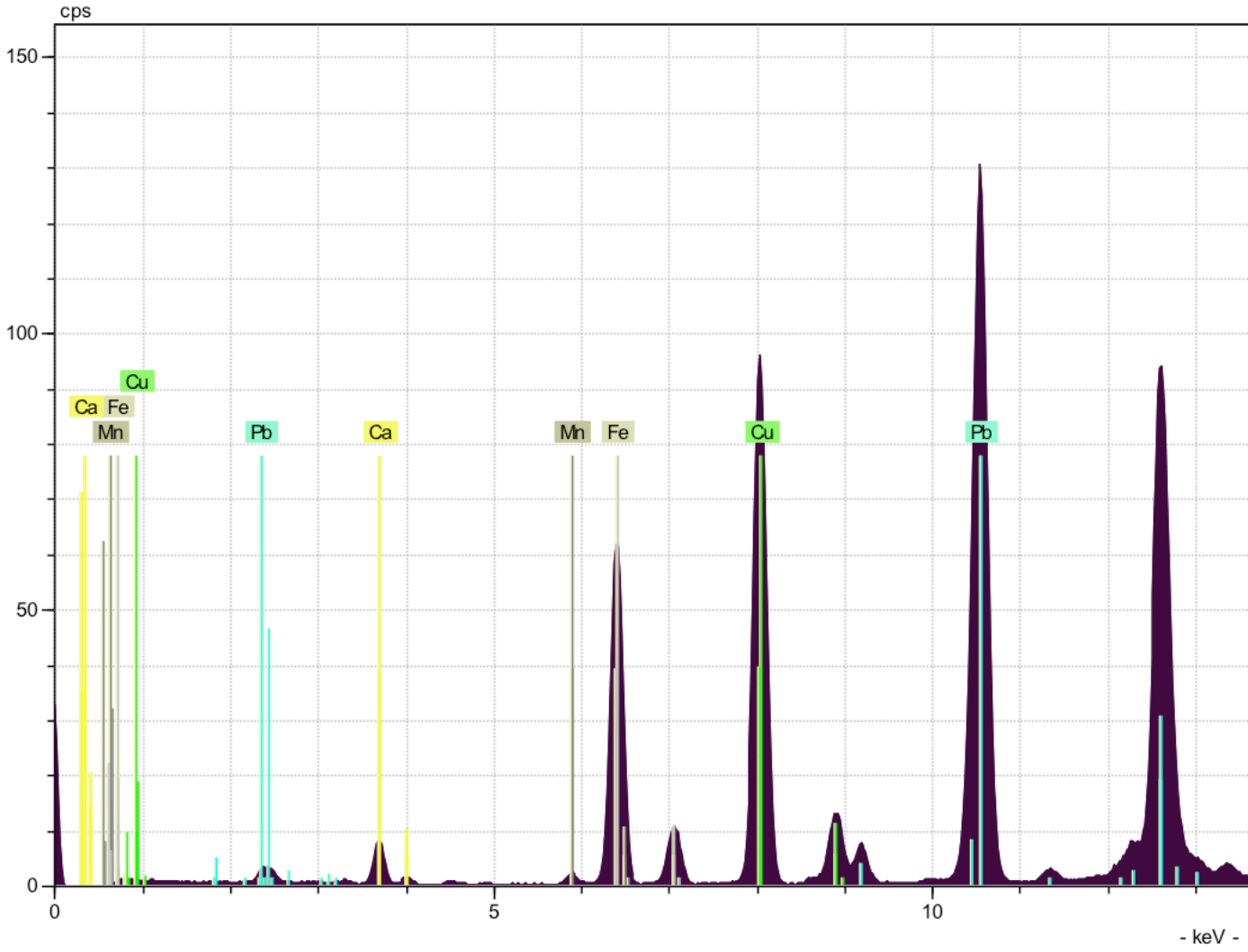
40 kV

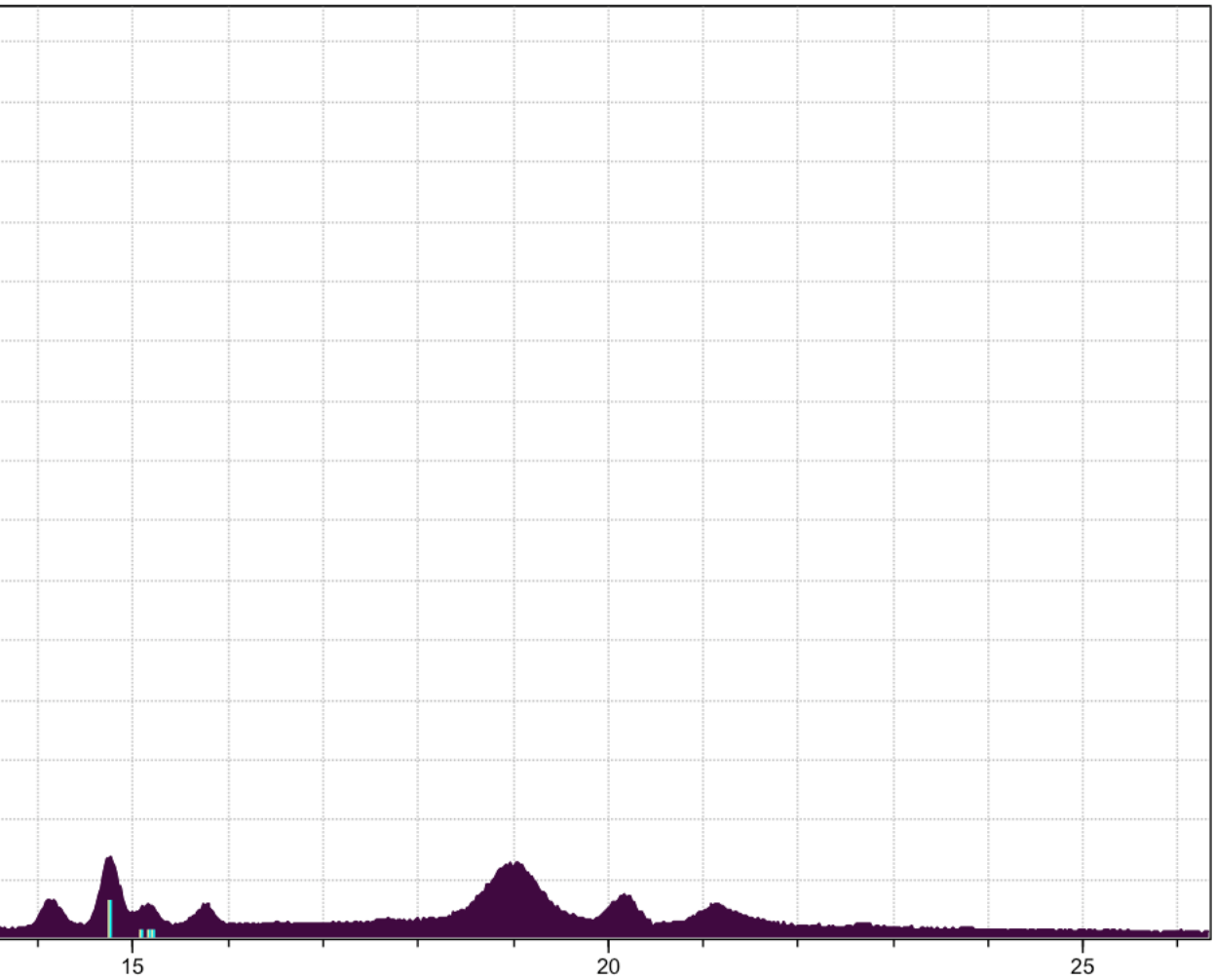
4.5 µA

air

filter: Ti 1 mil, Al 12 mil

time: 120 seconds




15
20
25

Location 48

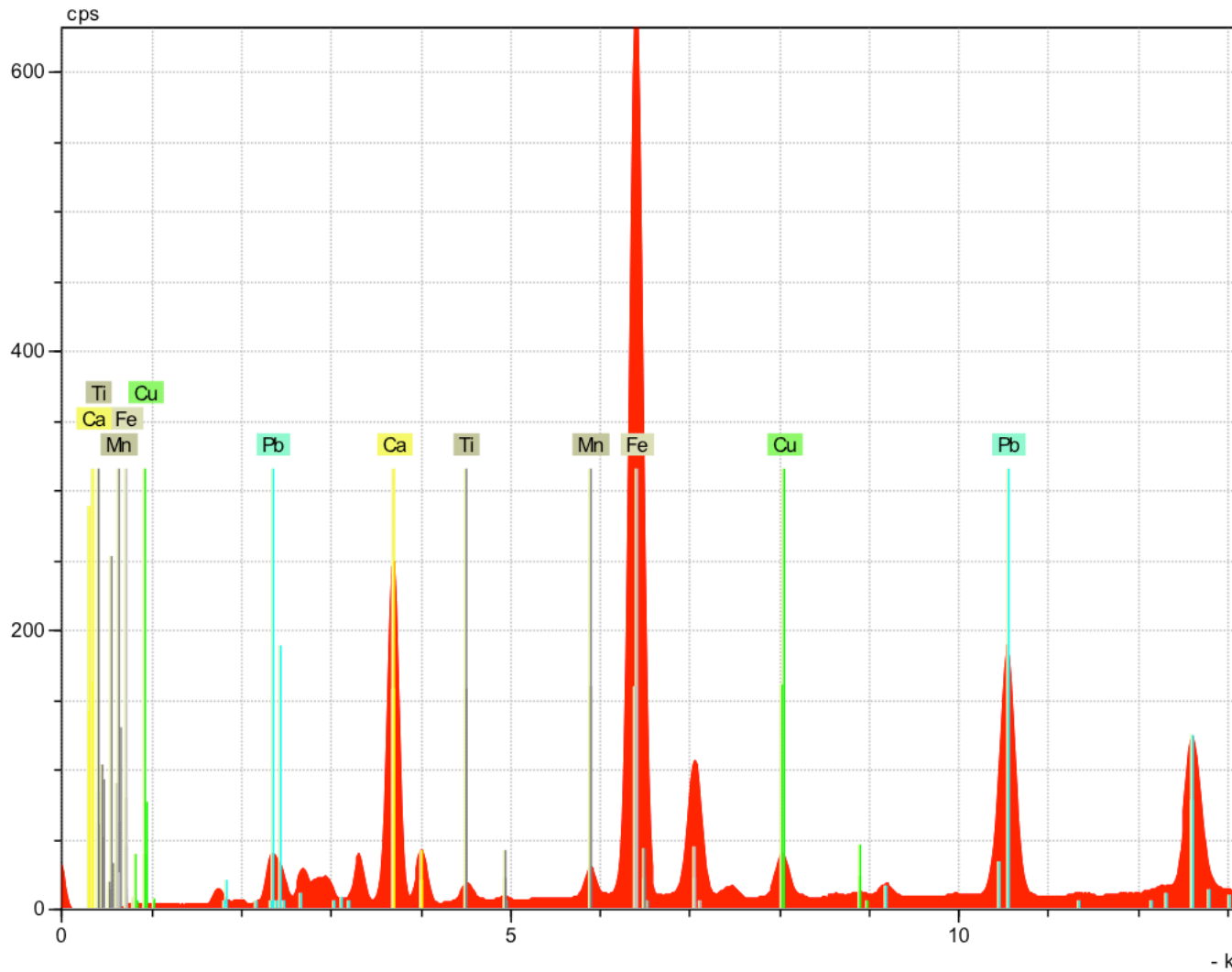
The soldier's thumb

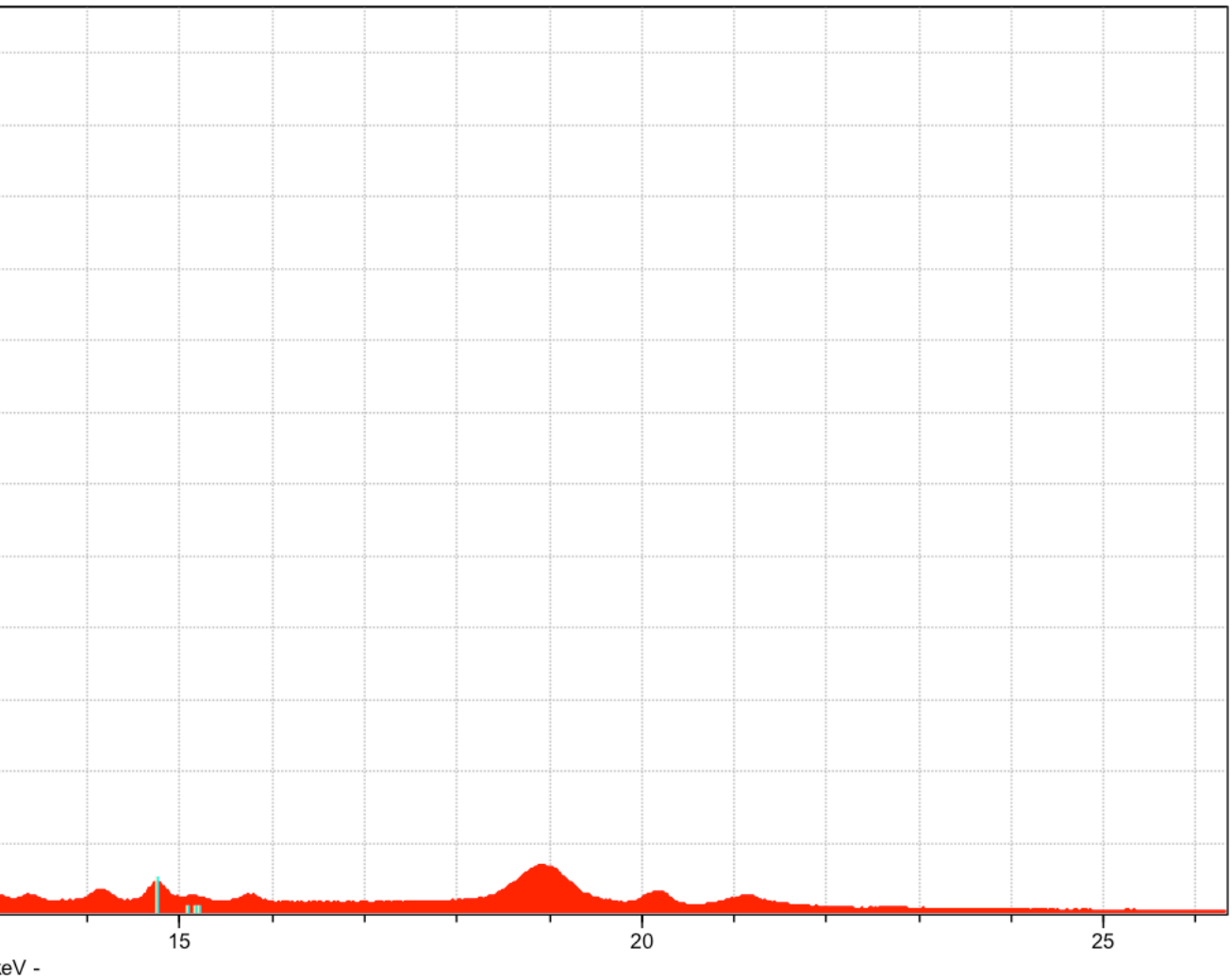
Notes / possible pigments

Possible copper-based pigment underneath thumb
or small amount added to darken the paint;
lead white; chalk; iron-based pigment; umber

Major intensity	Minor intensity	Trace intensity
Calcium (Ca)	Copper (Cu)	Manganese (Mn)
Iron (Fe)		Titanium (Ti)
Lead (Pb)		

40 kV
4.5 µA
air
filter: Ti 1 mil, Al 12 mil
time: 120 seconds




15
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keV -

End Notes

1. The Back-Vega version was previously in the collection of Emmerich and Christa Back-Vega, who presented the work as the original version in 1954. It is now in the Spier Collection in London and considered by some to be a second autograph version by Caravaggio. See Gianni Papi, *Caravaggio: The Back-Vega Crucifixion of Saint Andrew* (Milan: Skira, 2016), 28.
2. The count sent a number of artworks back to Spain in 1607 then again in 1610 after completing his term in Naples. For an in-depth discussion of the painting's history and travels from Naples to Spain, see Erin E. Benay, *Exporting Caravaggio: The Crucifixion of Saint Andrew*, Cleveland Masterwork Series 4 (Cleveland: Cleveland Museum of Art; London: Giles, 2017).
3. There are two inventory documents from 1653: January 3 and February 20. The former mentions four executioners in the painting, while the later inventory indicates three.
4. For more information on Arnaiz see http://www.arnaiz.com/castel.htm.
5. Anne Tzeutschler Lurie and Denis Mahon, "Caravaggio's *Crucifixion of Saint Andrew* from Valladolid," *Bulletin of the Cleveland Museum of Art* 64, no. 1 (1977): 12–13.
6. Alfonso E. Pérez Sánchez, *Caravaggio y el naturalismo español*, exh. cat. (Madrid: Raycar, 1973), cat. no. 4.
7. Lurie and Mahon, 10.
8. José Manuel Arnaiz founded the Instituto Técnico de Expertización y Restauración de Madrid in 1973, specializing in developing techniques for technical research and conservation.
9. Benedict Nicolson, "Caravaggio and the Caravaggesques: Some Recent Research," *Burlington Magazine* 116 (October 1974): 608.

9. Benedict Nicolson, "Caravaggio and the Caravaggesques: Some Recent Research," *Burlington Magazine* 116 (October 1974): 608.
10. Salerno and Mahon had authenticated two Caravaggio paintings in American museums: *Martha and Mary Magdalene* (Detroit Institute of Arts) in the 1960s and *The Crucifixion of Saint Andrew* (Cleveland Museum of Art) in the 1970s. See https://dictionaryofarthistorians.org/salernol.htm.
11. Lurie and Mahon, 13–15.
12. Ibid., 13. Also, theologian Joannes Molanus's scholarly research published in 1594 stated that the crux decussata was in error. See Henricus Cuyckius, ed., *De historia SS. Imaginum et picturarum pro vero earum usu contra abusus* (Louvain, Belgium, 1594), bk. IV, chap. LI, fol. 162v.
13. Jacobus de Voragine, *The Golden Legend of Jacobus de Voragine*, trans. Granger Ryan and Helmut Ripperger (Salem, NH: Ayer, 1969), 12–13.
14. The Nelson-Atkins Museum of Art in Kansas City has argued that their Caravaggio painting, *Saint John the Baptist in the Wilderness* (1604–5), was intended as an altarpiece. However, Ottavio Costa, who commissioned the painting for the altar of the oratory dedicated to Saint John the Baptist in Coscente, kept the original and sent a copy. See Sebastian Schütze, *Caravaggio: The Complete Works* (Cologne: Taschen, 2009), 268.
15. Ross Merrill, "Construction and Condition Report," February 17, 1976, Cleveland Museum of Art conservation files.
16. "Statement by Jan Dik on His Restoration of Caravaggio's 'Martyrdom of St. Andrew,'" March 20, 1976, CMA conservation files. There is no mention of the outcome of this treatment.
17. Canvas fibers from the original support, examined with a

17. Canvas fibers from the original support, examined with a polarized light microscope at the Cleveland Museum of Art, exhibit characteristics consistent with bast fibers, most likely linen.
18. Irene Emery, *The Primary Structures of Fabrics* (London: Thames and Hudson, 1994), 125–26. The English word *huckaback* may derive from traveling hucksters who peddled linens in the British Isles.
19. Ibid., 98. Diamond (or lozenge) twill patterns where both horizontal and vertical reversals of diagonals are evenly spaced and correlated, whether or not they create symmetrical diamond figures.
20. Marco Ciatti and Brunetto Brunetti, ed., *Caravaggio's Painting Technique: Proceedings of the CHARISMA Workshop* (Florence: Nardini Editore, 2012). See especially Claudio Seccaroni, "A New Survey of Caravaggio's Canvases and Preparatory Layers: Materials and Aesthetic Effects," 60.
21. Rossella Vodret, *Caravaggio: Works in Rome; Technique and Style* (Milan: Silvana, 2016), 1:23.
22. For an extensive survey of patterned fabrics see Seccaroni, "New Survey of Caravaggio's Canvases," 61.
23. Oil on canvas, 165 x 218.2 cm; Leonard C. Hanna Jr. Fund, 1960.117. For more information about the canvas weave, see Zahira Véliz, "A Painter's Technique: Zurbarán's *The Holy House of Nazareth*," *Bulletin of the Cleveland Museum of Art* 68, no. 8 (1981): 271–85.
24. Merrill's conservation report refers to Edoardo Arslan, *Nota Caravaggesca, Arte Antica e Moderna* 6 (April/June 1959): 212, figs. 1 and 2, where *Bacchus* is described as having a "complex diamonded-patterned fabric (five small diamonds within a larger diamond, which has four diamonds within a diamond at the intersections of the larger pattern)." *The Rest on the Flight into Egypt* is painted on a support with an even

diamond at the intersections of the larger pattern)." *The Rest on the Flight into Egypt* is painted on a support with an even more complex diamond design (five diamonds in a double cross within a diamond and four diamonds at the intersections of the larger diamond).

25. Twenty-eight X-ray films were inserted between the reverse of the lining canvas and stretcher bars, and exposed to 16 kilovolts (kV) and 3 milliamps (mA) for 210 seconds, the same exact settings used to produce the 1976 films. An additional eighteen films collected remaining X-ray information around the edges. The new X-rays were digitized and assembled in Photoshop to produce a seamless, high-resolution image. Individual X-rays were photographed on a light box using EquaLight™ software that compensates for possible uneven lighting, and then assembled manually in Photoshop.
26. Merrill, "Construction and Condition Report."
27. Preliminary stretching tests on modern plain-weave linen in the CMA conservation lab conducted with Jennifer Brunton, Master of Letters candidate, Centre for Textile Conservation and Technical Art History, University of Glasgow, demonstrated that greater cusping in the weft can be produced after stretching, preshrinking, and sizing, or restretching after preshrinking. These same tests indicated that in both cases less cusping was always seen in the warp.
28. Compare the measurements of the four paintings: Cleveland Museum of Art, 202.5 x 152.7 cm; Musée des Beaux-Arts, Dijon, 209 x 151.5 cm; Museo de Santa Cruz, Toledo, 232.5 x 160 cm; Back-Vega version, 200 x 150 cm.
29. The conservator of the Back-Vega version, Bruno Arciprete, estimates that the painting may have been trimmed by 5 to 6 cm in width and 10 to 11 cm in height, and was once closer to the dimensions of the Cleveland painting. See Papi, *Caravaggio: The Back-Vega Crucifixion of Saint Andrew*, 46.

to the dimensions of the Cleveland painting. See Papi, *Caravaggio: The Back-Vega Crucifixion of Saint Andrew*, 46.

30. Seccaroni, "New Survey of Caravaggio's Canvases," 62.
31. Bruno Arciprete, "Il restauro," in *La Flagellazione di Caravaggio: Il restauro*, ed. Denise Maria Pagano (Naples: Electa, 2004), 32.
32. These canvas inserts, of a type commonly used to span large areas of loss in old restoration treatments, were originally coated with a lead white ground layer and thus are visible in the X-ray.
33. Mark Bockrath and Barbara Buckley, "Illustrated Historical and Original Stretchers and Strainers," in *Painting Conservation Catalog*, vol. 2, *Stretchers and Strainers*, comp. Barbara Buckley (Washington: Paintings Specialty Group of the American Institute for Conservation of Historic and Artistic Works, 2008), 89, illus. 22.
34. Merrill, "Construction and Condition Report."
35. The first, lower, water-soluble ground layer varies in thickness between 200 and 700 micrometers (μm); the second, upper ground layer consistently varies between 100 and 200 μm.
36. Giorgio Vasari, *Vasari on Technique* (New York: Dover, 1960; first published 1550), 88. In the chapter "Of Painting in Oil on Canvas," 236–37, Vasari describes a mixture made from "flour and walnut oil with two or three measures of white lead put into it, and after the canvas has been covered from one side to the other with three coats of smooth size, this paste is spread on by the means of a knife, and all the holes come to be filled up by means of the artist."
37. The FTIR analysis, performed in collaboration with Gregory D. Smith of the Indianapolis Museum of Art's conservation science department, used the Thermo Nicolet 6700 spectrometer (transflection mode). A fragment from the

37. The FTIR analysis, performed in collaboration with Gregory D. Smith of the Indianapolis Museum of Art's conservation science department, used the Thermo Nicolet 6700 spectrometer (transflection mode). A fragment from the lower ground was placed on a MirrIR low-e microscope slide; deionized water dripped on the fragment leached out the water-soluble components.
38. Pyrolysis–gas chromatography–mass spectrometry (Py-GC-MS) analysis was positive for oil; however, the exact type has not been established at this time.
39. Equipment used: Zeiss Evo MA15 SEM under variable pressure conditions using a five-segment back-scattered electron detector or a Bruker Quantax 200 EDS detector. See individual cross sections for more information.
40. Pyrite framboids averaging 2 µm in diameter were discovered with SEM-EDX at 9,340x.
41. Matteo Positano, Irene Aliatis, and Claudia Conti, "Micro-Destructive Investigations," in Vodret, *Caravaggio: Works in Rome*, 1:313, fig. 3; 1:314, fig. 5.
42. Equipment used: Cleveland Museum of Art's Osiris infrared reflectography camera, indium gallium arsenide (InGaAs) detector array sensitive to 900–1,700 nanometers (nm).
43. Roberto Bellucci and Cecilia Frosinini, "New Evaluations on Caravaggio's Methods of Underdrawing: Art Historical and Scientific Challenges," in Ciatti and Brunetti, *Caravaggio's Painting Technique*, 51.
44. Ibid., 56.
45. Keith Christiansen, "Caravaggio and 'L'esempio davanti del naturale,'" *Art Bulletin* 68, no. 3 (1986): 421–45. Christiansen mentions "two incisions on the back of the man on the ladder, at left, just inside the contour of the white shirt," 436. In the 1976 conservation report, Merrill noted incisions corresponding to the shoulder and outer contour of the standing figure's torso.

45. Keith Christiansen, "Caravaggio and 'L'esempio davanti del naturale,'" *Art Bulletin* 68, no. 3 (1986): 421–45. Christiansen mentions "two incisions on the back of the man on the ladder, at left, just inside the contour of the white shirt," 436. In the 1976 conservation report, Merrill noted incisions corresponding to the shoulder and outer contour of the standing figure's torso.
46. *Abbozzo* is an Italian word for "sketch" now commonly used by Caravaggio scholars when referring to the underlying brushstrokes of lead white paint visible in X-rays and often through the finished paint layers.
47. Equipment used: Cleveland Museum of Art's Osiris infrared reflectography camera, indium gallium arsenide (InGaAs) detector array sensitive to 900–1,700 nm.
48. In "Caravaggio and 'L'esempio davanti del naturale,'" 436, Christiansen mentions that this cracking "may be the result of an underlying incision."
49. Equipment used: Cleveland Museum of Art's Osiris infrared reflectography camera, indium gallium arsenide (InGaAs) detector array sensitive to 900–1,700 nm.
50. Maria Beatrice De Ruggieri, "Caravaggio's Painting Technique: Compositional Processes and Material Structures," in Vodret, *Caravaggio: Works in Rome*, 117: "Far more evident in the two Cerasi canvases are the numerous dark brushstrokes outlining the figures, again clearly revealed by reflectography and present in other paintings very close to these, such as the *Madonna of the Rosary*."
51. Equipment used: Bruker Tracer III-SD handheld XRF spectrometer.
52. The green pigment in this area produced a strong copper peak using the handheld XRF spectrometer and the SEM-EDS. Malachite was confirmed by Raman spectroscopy. See cross section 9.
53. For more on the brown discoloration of copper resinate

53. For more on the brown discoloration of copper resinate green, see Hermann Kühn, "Copper Resinate (Transparent Copper Green)," in *Artists' Pigments: A Handbook of Their History and Characteristics*, ed. Ashok Roy (Washington: National Gallery of Art, 1993), 2:150.
54. See the SEM image and spectrum for particle (2) for cross section 15.
55. See layer (c) and elemental maps in cross section 2.
56. See XRF spectra for locations 9 and 10.
57. See the Raman spectrum for lead-tin yellow type II particles in cross section 11.
58. "Statement by Jan Dik." According to Mark Gottsegen, Griffin picture varnish "is a ketone resin solution in mineral spirits"; Gottsegen, *The Painter's Handbook* (New York: Watson-Guptill, 1993), 259. According to Gottsegen, James Hamm, professor of painting conservation at the State University of New York, Buffalo, reports in a private conversation that Griffin also contained some type of oil used as a plasticizer.
59. A resinous substance secreted by a scale insect (*Laccifer lacca*) and used chiefly in the form of shellac.
60. The Griffin varnish sample from the Detroit Institute of Arts was analyzed by Py-GC-MS using tetramethylammonium hydroxide (TMAH) derivatizing agent.
61. See overlapping elemental maps of sulfur and calcium of fill material for cross section 2.
62. Cross section 2 was coated first with diluted emulsion polymer (Rhoplex™ M200), then embedded in polyester resin (Bio-Plastic™).
63. Galdehyde resin solution is composed of Laropal® A 81 (a low-molecular-weight urea aldehyde resin) in a petroleum distillate mixture. Hereafter: Laropal.
64. Regalrez® 1094 is "100% hydrogenated oligomers of styrene and alpha-methyl styrene." See Jill Whitten et al., "Low

64. Regalrez® 1094 is "100% hydrogenated oligomers of styrene and alpha-methyl styrene." See Jill Whitten et al., "Low Molecular Weight Varnishes," in *Painting Conservation Catalog*, vol. 1, *Varnishes and Surface Coatings*, comp. Wendy Samet (Washington: Paintings Specialty Group of the American Institute for Conservation of Historic and Artistic Works, 1998), 109.
65. UV lamp source: Broncolor® Unilight 1600 lamp modified with a quartz glass inner dome designed to pass UV wavelengths and Broncolor® UV attachment that lets UV-A radiation and a small portion of UV-B in the range of 300–315 nm pass through. Camera: Sinar eXact view camera modified with a Kodak Wratten 2E filter and Kodak infrared cut-off filter no. 304.
66. The interpretation of the UV photograph after treatment was in consultation with Jiuan-Jiuan Chen, professor and imaging specialist in Buffalo State College's art conservation program.
67. One gram of 98% triammonium citrate acid dissolved in 100 ml of deionized water buffered with ammonium hydroxide to a pH of 6.5.
68. The aged sample of Griffin varnish from the Detroit Institute of Arts was analyzed with FTIR. The spectra did not indicate the presence of oil, likely due to its low concentration. An oil component was later detected with Py-GC-MS in the presence of TMAH. See also note 58: James Hamm mentioned that after it was known that Griffin contained a small amount of oil, many conservators abandoned its use as a picture varnish.
69. Solvent combinations that included a greater proportion of isopropanol or the addition of ethanol improved the dissolution, but also tended to drive the varnish coatings into the cracked and porous paint surface.
70. Modostuc, a commercial Italian spackling paste ideal for

mentioned that after it was known that Gamblin contained a small amount of oil, many conservators abandoned its use as a picture varnish.

69. Solvent combinations that included a greater proportion of isopropanol or the addition of ethanol improved the dissolution, but also tended to drive the varnish coatings into the cracked and porous paint surface.
70. Modostuc, a commercial Italian spackling paste ideal for filling losses and commonly used by conservators in Europe and the United States, is composed of calcium carbonate with small amounts of barium sulfate in a polyvinyl acetate (PVA) copolymer binder.
71. PVA conservation paints (Golden Artist Colors Inc.) modified with additional dry powdered pigments.
72. Twenty grams of dry resin (Laropal A 81) were dissolved in 100 ml of hydrocarbon solvents—a high-flash-point aromatic and a mineral spirit type (ShellSol A100/D38)—in a 1:2 ratio. Testing of slightly more dilute mixtures produced uneven surface gloss due to the surface porosity caused by areas of exposed ground and cracking.
73. Gamblin conservation colors are composed of powdered pigments ground with Laropal resin, compatible with the isolating varnish composed of the same resin.
74. Images made during treatment of the Back-Vega painting reveal that the conservator reconstructed a substantial amount of damage in the area of the soldier's mouth. Therefore, that painting did not provide particularly useful information for the reconstruction of this passage.
75. Images of the Back-Vega version during the cleaning are in Papi, *Caravaggio: The Back-Vega Crucifixion of Saint Andrew*, 59.
76. Ibid., 58–60.

Equipment and Materials

Bio-Plastic®: Aldon Corporation, Avon, NY

Bio-Plastic™: Ward's Science, Rochester, NY

Broncolor® Unilight 1600 lamp: Bron Elektronik AG, Allschwil, Switzerland

Colour Shaper® silicone brush tools: Royal Sovereign International, Rockleigh, NJ

Denton vacuum sputter coater, Desk IV model: Moorestown, NJ

EpoxiCure®2 epoxy resin: Buehler, Lake Bluff, IL

EpoxyCure™ epoxy resin: Epoxycure Corporation, Paoli, PA

EquaLight™ 3 software: Robin Myers Imaging, Pleasanton, CA

FTIR Thermo Nicolet™ 6700 spectrometer: Thermo Fisher Scientific, Waltham, MA

Gamblin Conservation Colors: Gamblin Artists Colors, Portland, OR

Laropal® A 81: BASF Corporation Chemicals Division, Parsippany, NJ, and Gamblin Artists Colors, Portland, OR

Modostuc spackling paste: Plasveroi International, Srl, Giovenzano, Italy

Onca-MWIR-InSb-640 infrared thermal camera: Xenics Infrared Solutions, Leuven, Belgium

Osiris infrared reflectography camera: Opus Instruments, Cambridge, UK

Polyvinyl acetate conservation paint: Golden Artist Colors, Inc., New Berlin, NY

Regalrez® 1094 hydrocarbon resin: Eastman Chemical Company, Kingsport, TN

Rhoplex™ Multilobe™ 200 emulsion polymer: Dow Chemical Company, Midland, MI

Sinar eXact view camera: Sinar Photography AG, Zurich, Switzerland

Tracer III-SD (handheld X-ray fluorescence spectrometer): Bruker Corp., Billerica, MA

Ultra-Flex Micro-Mesh™: Micro-Surface Finishing Products, Inc., Wilton, IA

Zeiss filters: Zeiss International, Oberkochen, Germany

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For a fascinating account of the complex history of this masterwork and its understudied position in Caravaggio's oeuvre, see Erin Benay, *Exporting Caravaggio: The Crucifixion of Saint Andrew* (Cleveland: Cleveland Museum of Art; London: Giles, 2017). Made possible in part by the Andrew W. Mellon Foundation.

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Heidi Strean, *Director of Exhibitions and Publications*
Rachel Beamer, *Publication Specialist*
Edited by Amy Sparks
Concept design by Thomas H. Barnard

Giles Limited

Dan Giles, *Managing Director*
Louise Parfitt, *Editorial Manager*
Alfonso Iacurci, *Art Director*
Michael Andreas, *Developer*

The Cleveland Museum of Art
11150 East Boulevard
Cleveland, OH 44106
clevelandart.org